High-Impact Weather Prediction Project (HIWPP)
First Year Accomplishments and Status

Executive Summary

This report is intended to summarize the interim progress (year 1) of the High Impact Weather Prediction Project (HIWPP). As one might surmise from the sheer length of this report alone, considerable progress has been made across the five major sub-projects, which are: (i) hydrostatic global models; (ii) non-hydrostatic global models; (ii) moving hurricane nests; (iv) NMME expansion; and (v) the test program. Each of the 19 task leads has contributed to this report.

Several initial and very significant milestones are on the project horizon. By early January the three high-resolution hydrostatic models are expected to be running in real-time, and the HIWPP Open Data Initiative (formerly Trusted Partners) will be kicked off shortly thereafter, making real-time data and visualization available publically and allowing them to provide feedback on the model development. Support of the Open Data Initiative has been prepared, including processes for registering users and collecting their feedback. Version 1.0 of the NEIS visualization system is working and ready for use by the greater community, and the HIWPP data system is in place. A web presence for HIWPP has been established and maintained.

The non-hydrostatic models group has completed the idealized test cases planned for year 1 of the project and prepared a report on the results. That report is included here as Appendix B. HIWPP is now well-coordinated with the NGGPS (R2O initiative) and the results from our HIWWP non-hydrostatic global modeling efforts will directly inform the selection of the dynamical core for the next generation operational global weather model.

The moving hurricane nest team is making good progress and meeting their milestones. They do not yet have visible deliverables but, as seen in their report, they are making good progress towards the deliverables that will be produced in year 2. The same is true for the NMME Expansion; one of their key milestones (archiving the enhanced data was delayed significantly) due to some technical issues, but is now progressing well. Their other work is progressing well in parallel and final results should not be affected in any way.

Given the delayed start and the advent of the NGGPS coordination, we completed a significant update to the project plan with re-baselined milestones. This has been reviewed and approved by the HIWPP Executive Oversight Board.

An important outcome of the HIWPP project, which is critical to advancing global model development in

this country, has been the collaboration between the many different participating teams and organizations. This has been maintained by 2 face-to-face meetings in the first year: one in Boulder, CO, and one in College Park, MD, which have facilitated critical dialogue between OAR, NWS, NCAR and NRL.

Contents

1 Introduction

Project Objectives:

Hurricane/Post-Tropical Cyclone Sandy called attention to the need to invest in and invigorate our numerical weather prediction infrastructure for the United States. In order to address this gap, Public Law 113-2, *"Disaster Relief Appropriations"*, provided $12,905K to NOAA to accelerate and enhance the development of new and improved global numerical weather prediction models through the High-Impact Weather Prediction Project (HIWPP). Reported here is the progress of the project through the first year of the program in FY2014.

HIWPP's overarching objectives are to:

- Improve the current generation (hydrostatic) of global numerical weather prediction models (NWP), run them at higher resolutions and for longer forecast periods (medium range and beyond), and generate new ensemble products.
- Accelerate the development of the next generation of (non-hydrostatic; cloud resolving) global NWP models for medium range forecasts.
- Develop and integrate new scale-aware physical parameterizations of key atmospheric processes, and a new approach to data assimilation known as four-dimensional ensemble-variational (4D-En-Var) assimilation into both the hydrostatic and non-hydrostatic models.
- Optimize models to run on state of the art computer systems, namely the massively parallel fine grain (MPFG)/graphical processing unit (GPU)-based computers.
- Create low latency tools built on high-speed networks to collect, access, extract, evaluate and visualize high resolution, gridded global earth information, and make it available to the broader weather community comprised of data users, and solicit their feedback.
- Embed even higher resolution models within our global models (nesting models), especially for key phenomena such as hurricanes, since many important processes occur at scales below even 3-4 km.
- Develop a seamless suite of forecasts of high impact weather events that extends to periods beyond 16 days (seasonal).

Project Structure:

To meet these objectives, the project was structured as 5 sub-projects, each of which was in turn comprised of one or more tasks. Figure 1-1 shows the work breakdown structure of the project. This report follows that work breakdown structure, with contributions from each of the sub-projects and tasks.

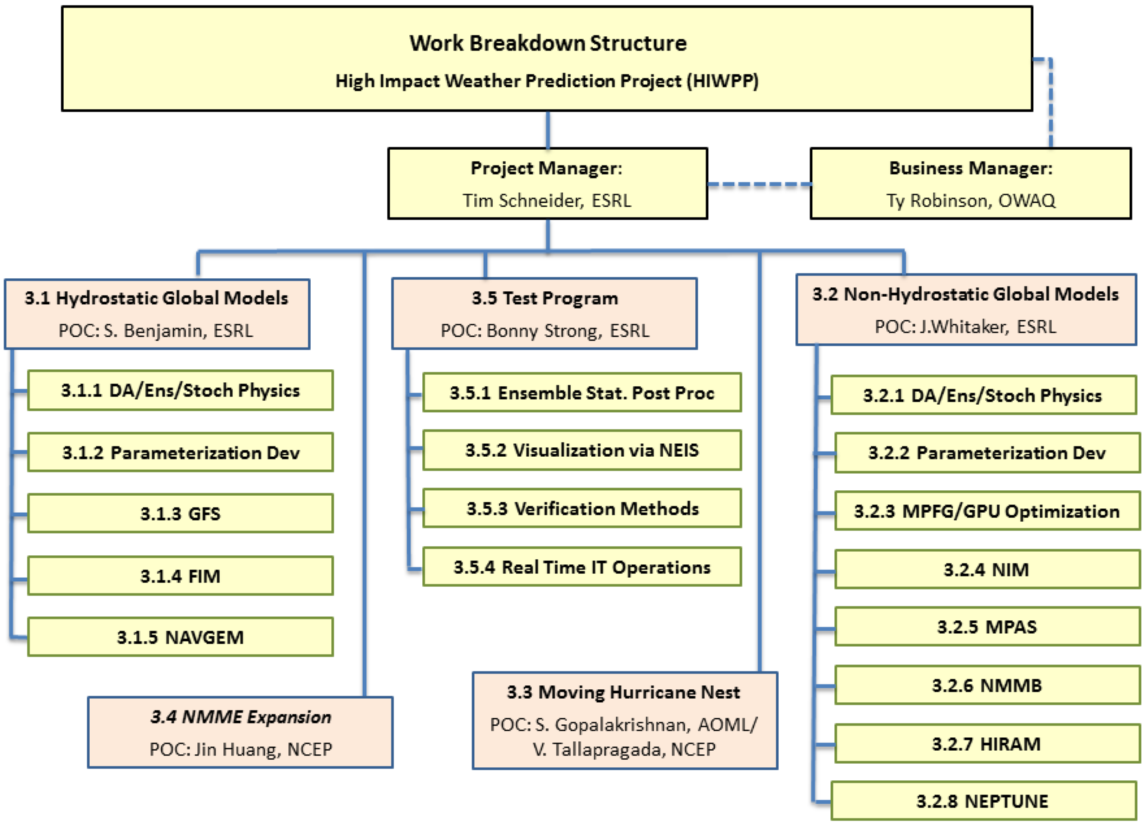


Figure 1-1 HIWPP Work Breakdown Structure. The 5 sub-projects are shown in orange boxes, and the tasks in the yellow boxes. Two sub-projects, 3.3 Moving Hurricane Nest and 3.4 NMME Expansion consist of a single task.

Oversight of the project is provided by the Executive Oversight Board (EOB), meeting monthly. As of October 1, 2014, the EOB was compromised of the following members:

- Robert Atlas, Director, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory
- John Cortinas, Director, NOAA/OAR Office of Water and Air Quality (Chair)
- Simon Chang, Superintendent, Naval Research Laboratory, Marine Meteorology Division
- Kevin Kelleher, Director, NOAA/OAR/ESRL Global Systems Division
- Alexander MacDonald, Director, NOAA/OAR Earth Systems Research Laboratory and OAR Chief Scientist
- John Murphy, Director, NOAA/NWS Office of Science and Technology
- V. Ramaswamy, Director, NOAA/OAR Geophysical Dynamics Laboratory
- Hendrik Tolman, Director, NOAA/NWS Environmental Modeling Center
- Robert Webb, Director, NOAA/OAR/ESRL Physical Sciences Division

Project Coordination:

Many of the tasks within the HIWPP Work Breakdown Structure depend on progress and results from other tasks. In order to maintain coordination over the entire project, 3 Science Team meetings were held throughout FY2014, with participation and reports from all sub-project and task leads. These included:

- Feb 14, 2014 – Full day meeting via teleconference
- May 13-14, 2014 – Onsite meeting held at NOAA/ESRL in Boulder, CO
- Sep 18-19, 2014 – Onsite meeting held at NOAA/NCEP in College Park, MD

In addition, monthly conference calls of the five sub-project leads were held and monthly reports to the EOB were provided by the project manager.

A project plan was prepared initially in November, 2013 and reviewed by an external review board. This plan was modified in response to reviewers' comments, then baselined in February, 2014 when funds were released. The plan was again reviewed in October, 2014 and re-baselined, primarily to align with new NOAA Research-to-Operations initiatives.

Financial Status:

The project period was originally planned to be 1 October 2013 – 30 September 2015. However, as project funds were not released until 14 February 2014, the project period was adjusted to be 14 February 2014 – 30 September 2016.

Due to the large number of grants associated with Sandy Supplemental funding and the careful oversight of this funding, grants to Cooperative Institutes took longer than expected to reach the institutes, with some not completed until June 2014. All project funds were obligated by the end of FY2014, including grants to Cooperative Institutes and contractors and major hardware purchases. Work through the Cooperative Institutes will permit extension of project tasks through FY2016.

Milestones Status:

Though funding was not released until February 2014 to the federal programs, and even later as grants to the Cooperative Institutes and contractors, all project members strived to meet the original milestones set for the first year of the project. In some cases, the late release of funds delayed hiring that was critical to completion of tasks, and thus delayed meeting a few milestones. However, except for the few delays caused by late hiring and delays of about one fiscal quarter in the implementation of the high-resolution hydrostatic models, the impressive efforts of all project tasks teams have led to completion of all other milestones set for year one of the project. The project has significant achievements to report as of the end of FY2014. A complete list of all milestones from the project plan and their status as of October 1, 2014 are included in Appendix A.

2 Sub-Project: Hydrostatic Global Models

Sub-project Lead: Stan Benjamin

2.1 Introduction

The Hydrostatic sub-project had a major portion of its deliverables due within year 1 of the project. With the compressed first year of the HIWPP project, team members in each of the five task areas have invested major efforts in order to meet the year-1 milestones and have succeeded with only minor delays. The great challenge of the first year was for the 3 participating hydrostatic model groups to improve their models to the highest resolutions possible, both spatially and temporally, and to be prepared to distribute this model data in a real-time research mode to outside users. Each of the modeling groups encountered challenges in modifying models to meet the targeted resolutions, but have overcome those challenges and are prepared to have models running in real-time research (or for GFS, operational) mode by mid-January of 2015.

In addition to the 3 hydrostatic modeling tasks, this sub-project includes 2 tasks that will advance capabilities in data assimilation, stochastic physics, and ensembling (task 3.1.1), and physics parameterization schemes (task 3.1.2) initially in the hydrostatic models. Later in the project these advances will be applied to the non-hydrostatic models. The 2 parts of the Parameterization task (3.1.2) were each dependent on hiring new staff to complete their planned deliverables, so were especially impacted when delays in the release of funding caused enforced delays in hiring. In spite of this delay, these tasks have made significant progress and expect to complete planned deliverables by the end of year 2. During year 1, research in these areas has been applied and tested within hydrostatic models. During the second year of the project, research results will be applied and tested for selected non-hydrostatic models.

2.2 Task 3.1.1 – Assimilation/Ensemble/Stochastic Physics

Task Leads: Jeff Whitaker and Tom Hamill

Data Assimilation:

HIWPP FY2014 assimilation work was focused on developing and testing a 4D Ensemble-Variational assimilation (4DEnVar) system for global prediction. This was a collaborative effort involving Lili Lei, Philip Pegion and Jeff Whitaker at ESRL, Rahul Majadan and Catherine Thomas at NCEP, and Daryl Kleist of the University of Maryland. The work at NCEP and University of Maryland was funded by a separate NWS Sandy-Supplemental project. The new 4DEnVar system involves a number of changes to the current operational 3DEnVar system. Firstly, the variational solver has been extended to include time-varying estimates of the background-error covariance (estimated from an Ensemble Kalman filter, or EnKF ensemble). This work was done by Daryl Kleist and colleagues at NCEP. Secondly, the GFS model was modified to include stochastic physics in order to better represent the model uncertainty of the background-error covariance estimated from the ensemble, especially its time variation. The GFS also was modified to include a four-dimensional incremental analysis (4DIAU) update capability, to more smoothly introduce time-varying analysis increments generated by 4DEnVar. Both of these tasks were completed by ESRL, and tested within the 4DEnVar system. Extensive testing and parameter tuning was done using a lower resolution version of the GFS model expected to become operational in Q1FY15. Results have shown a positive impact of both stochastic physics and 4DIAU within the 4DEnVar system. Work is now focused on configuring the 4DEnVar system for pre-implementation testing at NCEP starting at the beginning of the 2015 calendar year.

ESRL has also tested a balance constraint within the EnKF system to limit the production of gravity waves during the analysis cycle. The balance constraint was not found to be necessary since the 4DIAU is very effective at limiting imbalances in the analysis by slowly and smoothly introducing analysis increments into the forecast model. Several software infrastructure improvements were made by ESRL to the operational EnKF code repository at NCEP, including adding support for the NMM-B model and merging the EnKF code into the GSI project (to avoid code duplication and simplify code management and support). A strategy for tropical cyclone relocation within the EnKF system was also tested in collaboration with NCEP, and will be implemented as part of the Q1FY15 GFS analysis upgrade. Stochastic physics will also be implemented within the EnKF ensemble in the Q1FY15 upgrade. 4DEnVar with 4DIAU is planned for the next upgrade, in late FY15 or early FY16.

Stochastic Physics:

ESRL/PSD staff is now working collaboratively with EMC staff on parallel testing of a suite of stochastic physics parameterizations, including the "stochastically perturbed physical tendencies (SPPT) scheme from ECMWF, the "stochastic kinetic energy backscatter" (SKEB) scheme from ECMWF and UK Met Office, and an in-house method called "stochastically perturbed boundary relative humidity" (SHUM). After extensive development at ESRL, Walt Kolczynski at NCEP/EMC is now running parallel tests of the new methods relative to other baselines, including the current operational GEFS system, the parallel GEFS system expected to be implemented in Q1FY2015, a simulation with the parallel GEFS but without the current model uncertainty method, "stochastic total tendency perturbations" (STTP). Jan-Feb 2014 and Jun-Jul 2013 periods were used.

The summer 2013 verification statistics are available at

http://www.emc.ncep.noaa.gov/gmb/Walter.Kolczynski/sto_phys_s13/index.html
http://www.emc.ncep.noaa.gov/gmb/Walter.Kolczynski/sto_phys_s13/maps.html
while the winter 2014 verification statistics are available at
http://www.emc.ncep.noaa.gov/gmb/Walter.Kolczynski/sto_phys_w14/index.html
http://www.emc.ncep.noaa.gov/gmb/Walter.Kolczynski/sto_phys_w14/maps.html .

These results show that in most cases for the mid-latitudes, the new suite of stochastic physics has a neutral to mildly positive impact, including generally reduced RMS error and better spread-error relationships, especially for week +1. The improvements for the tropics are more significant, providing much better spread-error consistency. We view this project to be on track, with implementation anticipated in the GEFS in Q1FY2016, and with a peer-reviewed journal article produced in the next year. Special thanks are provided to Walt Kolczynski of NCEP/EMC, who has coordinated the testing at NCEP and who has moderated biweekly telephone conference calls to discuss results and underlying scientific issues.

Ensemble system development:

Gary Bates at ESRL/PSD has been exploring the impact of several methods of stimulating sea-surface temperature (SST) variability so as to increase near-surface temperature spread over oceans. The use of the "NSST" (Xu Li, NCEP/EMC) methodology for introducing a diurnal variation of ocean SST was explored, with that diurnal variability allowed to vary between different ensemble members based on different atmospheric forcings (different winds, near-surface temperatures, and insolation). The amount of increased medium-range spread was quite small. A larger amount of spread was introduced by introducing variability in the initial ocean SSTs. Further experiments are continuing at ESRL, including using a spatially dependent grid of estimated SST errors to modulate the size of the introduced SST perturbations. Pending successful further development, our expectation is that the SST perturbations can be incorporated into the Q1FY2016 GEFS implementation. Discussions with NCEP/EMC on such topics are ongoing.

Maria Gehne has led ESRL/PSD's exploration of ways of introducing more variability to the GEFS near-surface temperatures and humidities. There is a known sensitivity of surface temperature and precipitation forecasts to the analyzed soil moisture state, and this analyzed soil moisture state is largely determined through a land-data assimilation scheme that incorporates estimates of analyzed precipitation. Gehne has been examining a variety of precipitation analyses from various centers and using various data sets, and has found notable variability. The next step will be to work with the land-data assimilation team of NCEP/EMC to test drive parallel land data assimilation schemes with different precipitation analyses. Thereafter, we will examine the effect on medium-range forecasts from initializing from the different soil moisture analyses.

2.3 Task 3.1.2 – Parameterization Development

Task Leads: Georg Grell and Tom Hamill

(1) Unified representation of turbulence and clouds

The work under this sub-task has been delayed by roughly 3-6 months due to delays in hiring following from the delayed release of funds. Effective from July 15, 2014, the open position was filled by Alexei Belochitski. His previous experience at NCEP has enabled him to make rapid and efficient progress since then.

A novel unified representation of sub-grid scale (SGS) turbulence, cloudiness, and shallow convection is being implemented into the NOAA NCEP Global Forecasting System (GFS) general circulation model. The approach, known as Simplified High Order Closure (SHOC), is based on predicting a joint PDF of SGS thermodynamic variables and vertical velocity and using it to diagnose turbulent diffusion coefficients, SGS fluxes, condensation, and cloudiness. Unlike other similar methods, only one new prognostic variable, turbulent kinetic energy (TKE) needs to be introduced, making the technique computationally efficient.

As a first step of implementation, prognostic TKE equation is added to GFS in a non-interactive manner, and resulting TKE, eddy diffusivity and viscosity fields are analyzed. Modifications to GFS required for this step are to a large degree complete. Next, the assumed PDF component of SHOC will be introduced to GFS in a non-interactive mode, and its output will be analyzed. Finally, SHOC will be coupled to the host model to replace its current boundary layer, shallow convection, and large-scale condensation schemes and the resulting model will be tuned and evaluated following the standard procedure used at NOAA NCEP.

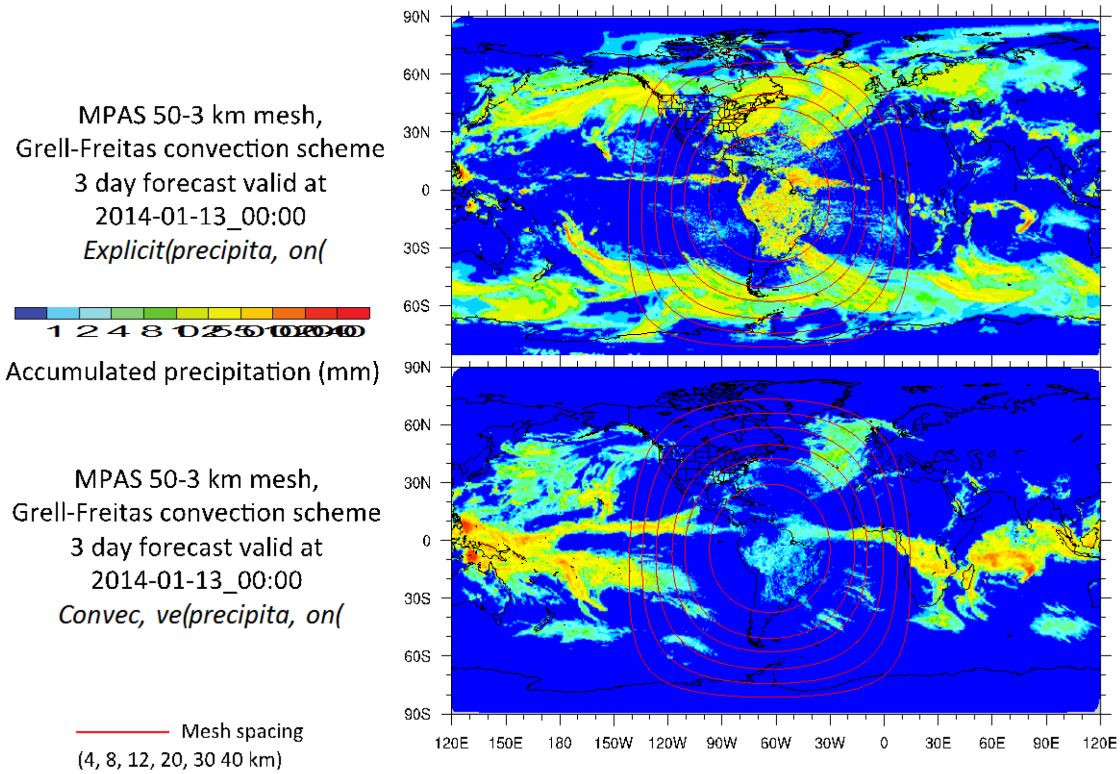
(2) Scale and aerosol aware stochastic convective parameterization

NOAA is working to develop a Next Generation state-of-the-art Global Prediction System expected to be applicable across a wide range of horizontal resolutions ranging from 1-100 kilometers. At these resolutions, the development of physically based parameterizations of subgrid convection will be a priority, particularly using scale aware, stochastic, and/or PDF-based approaches. Over the past decade, a new advanced convective parameterization was developed at NOAA/ESRL by Grell and Freitas (GF, 2014) that is both scale aware, and aerosol aware. This parameterization scheme is based on previous work (Grell 1993, Grell and Devenyi, 2002), will run in the operational implementation of the Rapid Refresh (RAP), and has been successfully used for hurricane simulations (Sun et al. 2014).

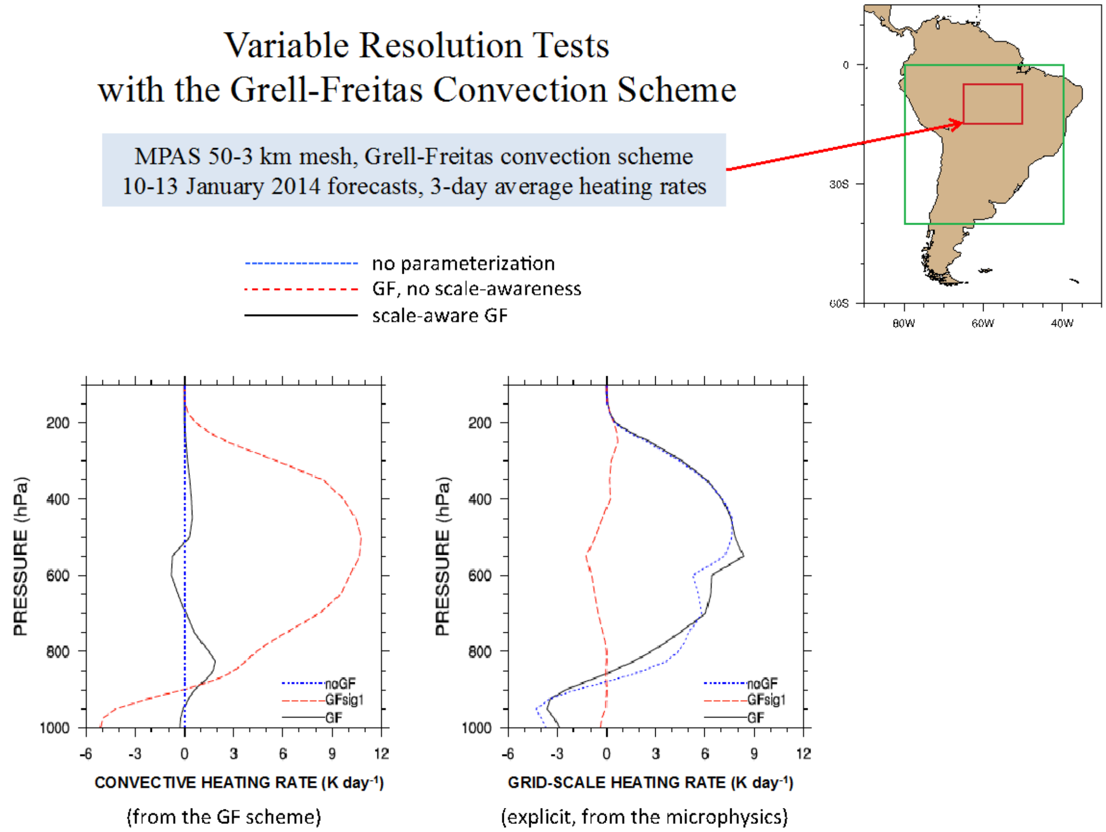
For HIWPP, this scheme is tested within hydrostatic and non-hydrostatic global modeling systems, and will be evaluated in real-time, in comparison to the SAS scheme used in the GFS physics suite. It is currently being tested in the GFS physics suite in the FIM as part of the High Impact Weather Prediction Project (HIWPP). GF is also directly related to the SAS scheme, which was developed using Grell (1993). Compared to the original implementation in the Weather Research and Forecast model (WRF), we felt that additional modifications were necessary for global applications. First, momentum transport was implemented in two different approaches: one as proposed in SAS, based on a paper by Zhang and Wu (2003), the other as implemented by ECMWF, based on Gregory (1997). Based on 1d comparisons with GATE soundings (provided by P. Bechtold) we chose the SAS approach, although the other approach will still be tested within the FIM over a longer time period. Additionally, recent new ideas from Bechtold et al (2014) related to a new diagnostic convective closure have also been implemented in GF for the HIWPP project. Bechtold et al (2014) demonstrated that this new approach is able to improve the representation of non-equilibrium convection such as the diurnal cycle of convection, leading not only to a more realistic phase representation of convection, but also to better spatial distribution and intensity. A few other SAS features were also considered valuable and included in the new version of GF.

The key feature of the Grell-Freitas (GF) scheme is that the role of the subgrid-scale parameterization is reduced as grid length decreases. This feature was tested in the original publication (Grell and Freitas, 2014), and has now also been shown in MPAS. Figure 3.1.2-1 shows a simulation of MPAS using GF on a variable resolution grid, with 3km horizontal resolution on the innermost grid over South America, and 50km resolution over most of the globe. On the coarser resolutions, much of the precipitation is convective, while over the high horizontal resolution inner domain most of the precipitation even over the tropical Amazon region is explicit. The transition across the scales appears smooth. Figure 3.1.2-2 shows a comparison of GF with scale awareness turned off versus scale awareness turned on and a simulation over the high resolution part of the domain where convective parameterization is turned off altogether. Without scale awareness, it is interesting to note that the parameterization – in the domain average – produces the heating maximum at about the same level as the explicit microphysics module. Even more interesting though, is the performance when scale awareness is turned on. The tendencies from the GF scheme become very small, as expected, but when combined with the grid scale heating lead to almost identical heating profiles as produced by the simulation without any convective parameterization. GF is currently being evaluated within the FIM in terms of height anomaly correlations for longer time periods.

The GF scheme also includes the capability to interact with aerosols through the conversion of cloud water to rain and evaporation of raindrops. We have started to look at this capability as part of a Working Group of Numerical Experimentation (WGNE) that is focused on aerosol impacts on numerical weather prediction.



3.1.2-1 GF scheme in global MPAS non-hydrostatic model, using variable resolution.



3.1.2-2 Averaged heating rates of runs using no convective parameterization (noGF) versus using GF with scale awareness turned off (GFsig1) and GF with scale awareness turned on (GF). Shown are heating rates from the convective parameterization (left) and the microphysical parameterization (right).

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2.4 Task 3.1.3 – GFS

Task lead: Yujian Zhu

In the past year, EMC staff has been working toward a high resolution (T1534L63 - approximately 13km in horizontal resolution) GFS with semi-Lagrangian for time integration and improved model physics. The new GFS has been implemented on January 14, 2015. Full retrospective runs from May 15, 2013 to current have been completed. In addition, the retrospective forecasts of two hurricane seasons (May 8 - Nov. 6, 2012, and May 20 - Nov. 20, 2011) which include the Sandy case have been finished. All model outputs (and initial conditions) have been saved on tape (HPSS mass store) for future comparison to other model forecasts (FIM and NAVGEM).

EMC staff members are also working on the next generation of the global ensemble forecast system (GEFS) which is based on the new GFS with lower horizontal resolution (T574L64 - approximately 34km). The next steps for GEFS development are to use EnKF 6-hr forecasts as bases of initial perturbations, apply tropical storm relocation and centralization, and tune stochastic total tendency perturbations (STTP) for model integration. One year of full ensemble retrospective runs (once per day) have been finished and all forecasts and initial perturbations have been archived to HPSS for ESRL and NRL to initiate their global ensemble system and future multi-model evaluation. GEFS is tentatively scheduled for implementation in April 2015. EMC has hired a contract scientist (Dr. Wei Li) from September 2014 to continue GEFS retrospective runs.

EMC has advertised to hire another contract scientist who will start ensemble post-processing from the multi-model system when ESRL (and NRL)'s ensemble forecasts are available.

2.5 Task 3.1.4 – Flow-Following, Finite Volume Icosahedral Model (FIM)

Task Lead: Stan Benjamin

The FIM team has focused on modifications required to use initial conditions from the GFS T1534 analysis from retrospective runs, in place of the GFS T574 analysis previously in use. This presented some challenges in modifying software to correctly interpolate to the native grid, but the upgrade was successfully completed and tested. The software team also implemented improved momentum interpolation code and new edge value interpolation. The science team continually analyzes model output to ensure no errors have been introduced by model upgrades and to optimize forecast performance, making use of advancements in verification produced by HIWPP task 3.5.3.

The advanced software team analyzed and optimized FIM code in order to output forecast data at a rate that could support hourly global forecasts. Also, in order to migrate from 6-hourly forecasts to hourly forecasts, an additional output variable was created so that both hourly and 6-hourly precipitation accumulations could be reported.

Comparison of physics packages has been a focus for the team over this year, in order to achieve optimal model performance. Experiments have compared GFS 2011, GFS 2012, GFS 2014, and Grell-Freitas physics schemes. For the beginning of the HIWPP real-time research runs, the team determined that the best option was to continue with GFS 2011 physics, but upgrades are anticipated in the near future to use either or both of GFS 2014 physics and the Grell-Freitas physics.

The FIM team has also been analyzing results from ensemble runs, comparing the current operational Global Ensemble Forecast System (GEFS) outputs to an experimental ensemble where half of the GEFS members have been replaced with FIM members. This work will form the basis of testing by NCEP in FY15 to potentially include FIM members in either the operational North American Ensemble Forecast System (NAEFS) or the operational GEFS.

2.6 Task 3.1.5 Navy Global Environmental Model (NAVGEM)

NRL's HIWPP hydrostatic model work for FY2014 has focused on building the input and output infrastructure required to ingest the shared initial conditions and to provide output data in a common format. The NRL team has completed a conversion suite that takes the model output in its traditional format and converts it to the GRIB2 format agreed to by HIWPP participants; this has already been used successfully for other projects as well.

On the input side, they have leveraged previous development at NOAA ESRL to better understand the incoming initial condition file format and unpack the initial conditions in a suitable condition for conversion to NAVGEM initial conditions. Current work focuses on converting the initial conditions to a form compatible with the NAVGEM forecast model. The NAVGEM configuration was modified to accommodate a lower model top than is used in Navy operations to be consistent with other HIWPP hydrostatic model participants.

3 Sub-Project: Non-Hydrostatic Global Models

Sub-Project Lead: Jeff Whitaker

3.1 Introduction

NCEP's current operational global atmospheric model dynamical core is approaching a grid spacing at which non-hydrostatic effects become significant, and may also not be able to scale up to the size of peta-scale HPC systems. Transitioning a new dynamical core (dycore) into operations is difficult and costly; therefore the NWS needs to carefully evaluate potential candidate non-hydrostatic dynamical cores to ensure a new dynamical core can serve NOAA's needs for at least 20 years. During year 1 of the HIWPP project 5 dynamical cores each ran a series of idealized test cases. The results of these tests are summarized in the report included as Appendix B of this report.

Two tasks in this sub-project, 3.2.1 and 3.2.2, will advance capabilities in data assimilation, ensembles, stochastic physics, and parameterization schemes. As noted in the section for the Hydrostatic Models sub-project, during year 1, research in these areas has been applied and tested within hydrostatic models. During the second year of the project, research results will be applied and tested for selected non-hydrostatic models.

Task 3.2.3 is dedicated to achieving maximum gains in model performance on newer high performance computing architectures. In order to run models at the high resolutions achievable with non-hydrostatic models, the large increases in compute power provided by Massively Parallel Fine Grain (MPFG) architectures are essential. To achieve the performance gains potentially available from MPFG architectures, parallelism within model software must be maximized. Task 3.2.3 focuses on code optimizations for non-hydrostatic models and benchmarks for evaluating and comparing different hardware architectures and different dynamical cores.

3.2 Task 3.2.1 – Assimilation/Ensemble/Stochastic Physics

Task Leads: Jeff Whitaker and Tom Hamill

See Task 3.1.1 under Hydrostatic Global Models

3.3 Task 3.2.2 – Parameterization Development

Task Leads: Georg Grell and Tom Hamill

See Task 3.1.2 under Hydrostatic Global Models

3.4 Task 3.2.3 – MPFG/GPU Optimization

Task Lead: Mark Govett

Significant progress was made on the fine-grain computing sub-task that supported both planned procurement of a fine-grain system, and ability to use such a system by one or more candidate dynamical cores. In addition, planned work to parallelize portions of routines from the WRF and GFS physics for fine-grain architectures was completed. Details of these activities are given below.

Hardware Procurement: The schedule to procure a fine-grain computer was dependent solely on the NIM model and served as a basis for performance evaluation of CPU, GPU and MIC based systems proposals by vendors. As a result, the first HIWPP task, to deliver a benchmark code to vendors by January 2014, was required prior to funding to support this activity. However, staff was successful in preparing model code, detailed instructions and documentation, and preparing data sets so vendors could install, and make specific runs of the NIM model on their computing systems.

Performance: Staff continued work on model performance targeting the latest hardware from Intel (MIC) and NVIDIA (GPU) as part of an ongoing and successful effort to evaluate hardware, compilers and other tools essential to run in fine-grain computing environments. In particular, a fourth evaluation of the industry standard OpenACC compilers from Cray and PGI was completed in the summer of 2014. The latest evaluation showed NOAA's in-house compiler, called F2C-ACC, continues to significantly outperform the commercial Fortran GPU compilers from Cray and PGI. In this evaluation, the F2C-ACC compiler ran NIM model dynamics 1.9 and 2.1 times faster than the Cray and PGI compilers. These results were shared with the vendors along with model code and suggestions for improvement. As a result of this work, both Cray and PGI are working hard to identify and overcome performance bottlenecks with a goal of beating the performance benchmark established by the F2C-ACC compiler. Recent updates suggest vendor improvements will be available in the January 2015 releases of the respective compilers.

In collaboration with Intel, we also improved performance of the NIM model running on the Intel MIC. Optimizations for GPU and MIC also led to further performance speedup on the traditional CPU architectures. Results for single-node performance were prepared for CPU, GPU and MIC and shared with vendors, detailing a snapshot in time of the current state of vendor hardware. To our knowledge, NIM is the only meteorological model capable of running on all three architectures, and this is done using a single version of the NIM source code. These performance results were shared with Intel, NVIDIA, PGI and Cray and posted to the web (http://www.esrl.noaa.gov/gsd/ab/ac/NIM-Performance.html). The results for Node-to-Node comparison are shown in Figure 3.2.3-1.

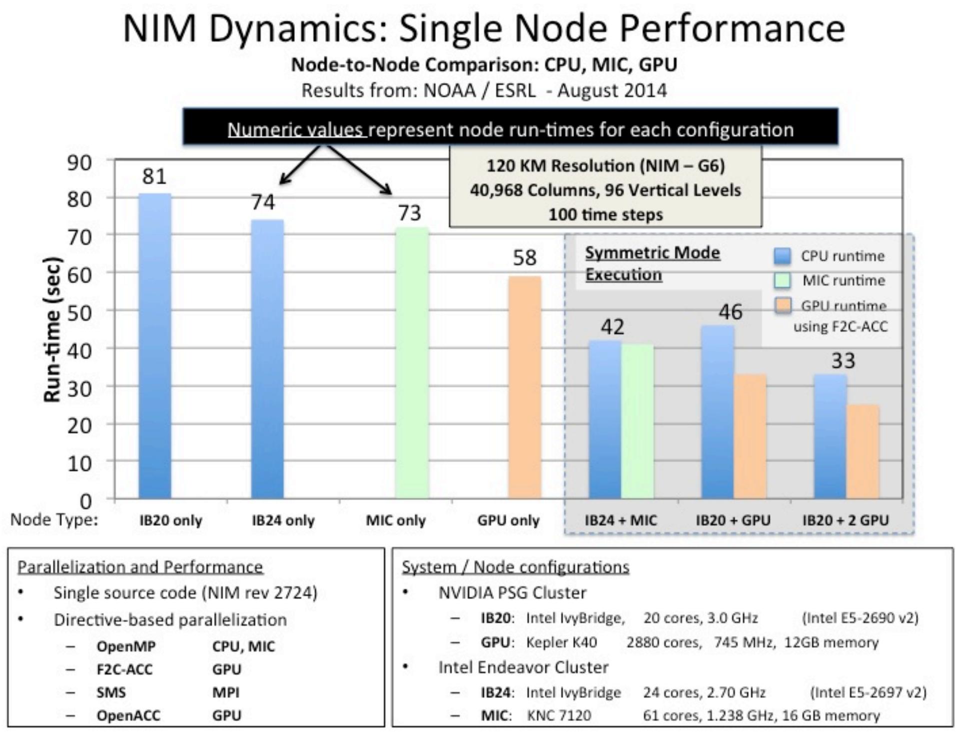


Figure 3.2.3-1 Performance results for NIM Dynamics on CPU, MIC, and GPU architectures

NIM dynamics has been optimized to thousands of nodes using TACC and ORNL resources. The benchmark version of the code, to be used for computational readiness testing for the NGGPS project, has been run on over 200,000 cores of titan (~13,000 nodes). It has also demonstrated good scaling and 96% parallel efficiency running on 40,000 cores of the TACC system (~2500 nodes).

Physics:

Progress towards physics parallelization was made for several routines from the WRF physics (micro-physics and short-wave radiation). Work on the WRF WSM6 microphysics targeted the GPU and MIC processors. To date, work on short-wave radiation has focused on the MIC, with GPU parallelization planned. The results show respectable performance but neither GPU nor MIC runtimes were faster than the latest generation Intel Haswell processor. The results are viewed positively however, because new fine-grain chips are expected to be significantly faster than the Haswell and thus will show favorable fine-grain performance in the future.

In addition, recent work has begun to parallelize the 2014 GFS physics for MIC. This work is expected to be relevant for GFS, NIM, MPAS and potentially other dynamical cores in 2015.

Publications:

In 2014, HIWPP web pages were developed that included input from ESRL and NCEP detailing fine-grain work and progress that was posted on the HIWPP web site (http://HIWPP.noaa.gov/hpc/). Finally, a peer-reviewed paper titled *Parallelization of the NIM Weather Model for GPUs* was accepted for presentation and publication at the annual and prestigious SuperComputing conference at a workshop on accelerator programming using directives (http://www.openacc.org/WACCPD14). The paper by Govett, Middlecoff and Henderson compares performance of the NIM model on GPUs using the F2C-ACC, Cray and PGI GPU compilers, and raised concerns about the OpenACC standard itself.

3.5 Task 3.2.4 – NIM

Task Lead: Jin Lee

See non-hydrostatic models test report in Appendix B

3.6 Task 3.2.5 – MPAS

Task Lead: Bill Skamarock

See non-hydrostatic models test report in Appendix B

3.7 Task 3.2.6 – NMMB

Task Lead: Zavisa Janjic

See non-hydrostatic models test report in Appendix B

3.8 Task 3.2.7 – HIRAM

Task Lead: Shian-Jiann Lin

See non-hydrostatic models test report in Appendix B

3.9 Task 3.2.8 – Navy Non-Hydrostatic Model (NEPTUNE)

Task Lead: Jim Doyle

See non-hydrostatic models test report in Appendix B

4 Sub-Project: Moving Hurricane Nest

Task 3.3

Sub-Project Leads: Sundararaman Gopalakrishnan and Vijay Tallapragada

(1) Project Goals

NOAA's High Impact Weather Prediction Project goal is to develop a system that can produce 10-day forecasts at ~3-km global resolution fast enough to meet operational requirements by the end of the decade, with forecast skill exceeding that of the updated hydrostatic GFS and other chosen baselines. Specific to hurricane predictions, the high-resolution operational Hurricane Weather and Research Forecasting (HWRF) model with a storm-following nest operating at 3km resolution is now used for real-time tropical cyclone (TC) forecast guidance for all global oceanic basins. The storm-centric HWRF model has proven value for track, intensity and structure predictions, and has been showing consistent forecast improvements in the past three years. The aim of this Hurricane Moving Nest sub-project is to leverage NOAA's success with the HWRF modeling system and accelerate progress towards creating a high resolution, next generation TC model with multiple moving nests operating at 3 km or higher resolution that is capable of providing simultaneous forecasts of several storms, improved multi-scale storm-storm interactions and land-storm interactions for more accurate TC forecasts. This system would have the potential to transition to next generation, regional (basin-scale), and eventually global, operational TC prediction system by the end of this project.

(2) Significant developments

(i) Proof of concept of Global tropical cyclone model with multiple moveable nests placed around all tropical systems in the world: Figure 3.3-1 shows the 48th hour forecast from a five-day simulation initialized on 08/30/2010 at 00Z of the Global NMMB in NEMS framework configured at uniform 27 km resolution. Embedded in this Global model are 5 sets of two way interactive, telescopic moving nests at 9 and 3 km resolutions (shown outlined in white boxes) for capturing inner core structure of TCs Danielle, Earl and Fiona in the Atlantic, and Lionrock and Kompasu in the West Pacific. The black line shows the 5-day forecast tracks from the moving nests. The insets show predictions of 10-m wind at 3 km resolution for 4 of the TCs in the global domain.

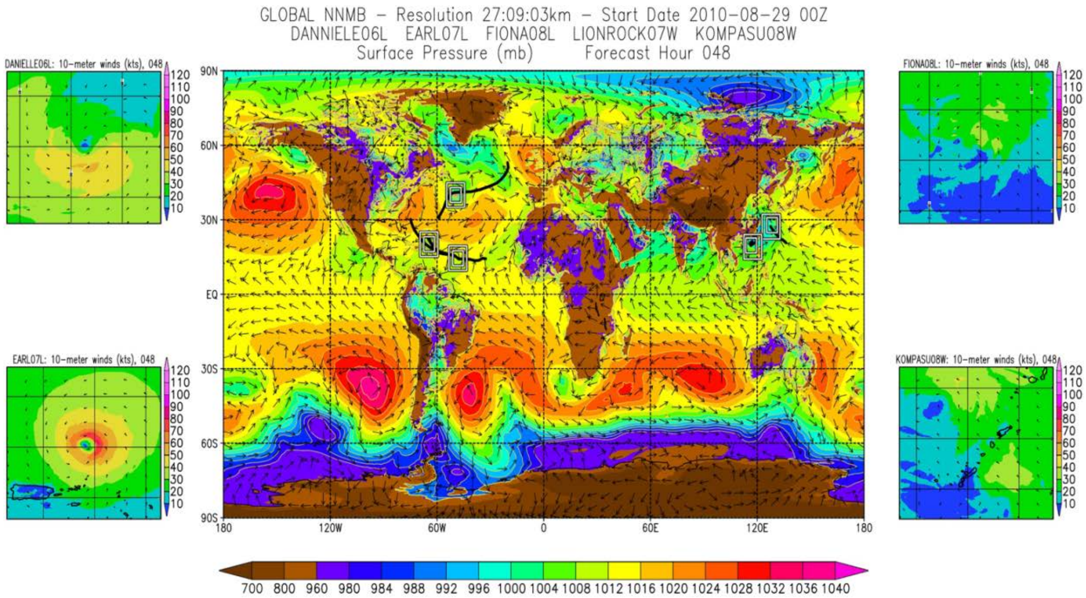


Figure 3.3-2 shows the 48th hour forecast from a five-day simulation initialized on 08/30/2010 at 00Z of the Global NMMB in NEMS framework configured at uniform 27 km resolution.

(ii) Transition HWRF Physics to NMMB/NEMS: One of the major objectives of this project is to transition the HWRF capabilities into the Nonhydrostatic Multiscale Model on B-grid/NOAA Environmental Modeling System (NMMB/NEMS) framework for multi-scale hurricane forecast applications and demonstrate superior forecast performance for hurricane track, intensity and structure (match or exceed current operational HWRF), with additional focus on landfall applications, rainfall, and size forecasts. As a first step towards transitioning HWRF developments into NMMB in the NEMS framework, all the TC specific physics schemes from HWRF have been implemented in the NMMB system and tested for their effectiveness. The latest EMC NMMB trunk update added the following schemes to the NMMB system:

- GFDL/HWRF surface layer and slab land model
- GFS/HWRF PBL for hurricanes
- SAS convection scheme for hurricanes
- MESOSAS scale-aware convection scheme
- New options/parameters for HWRF Physics in the configure_file for NMMB

The other HWRF schemes such as Ferrier microphysics and GFDL radiation (longwave and shortwave) are already available in the NMMB system. The effectiveness of HWRF physics in NMMB is tested by an example shown in Figures 3.3-2 and 3.3-3 from a real-time simulation of Hurricane Arthur.

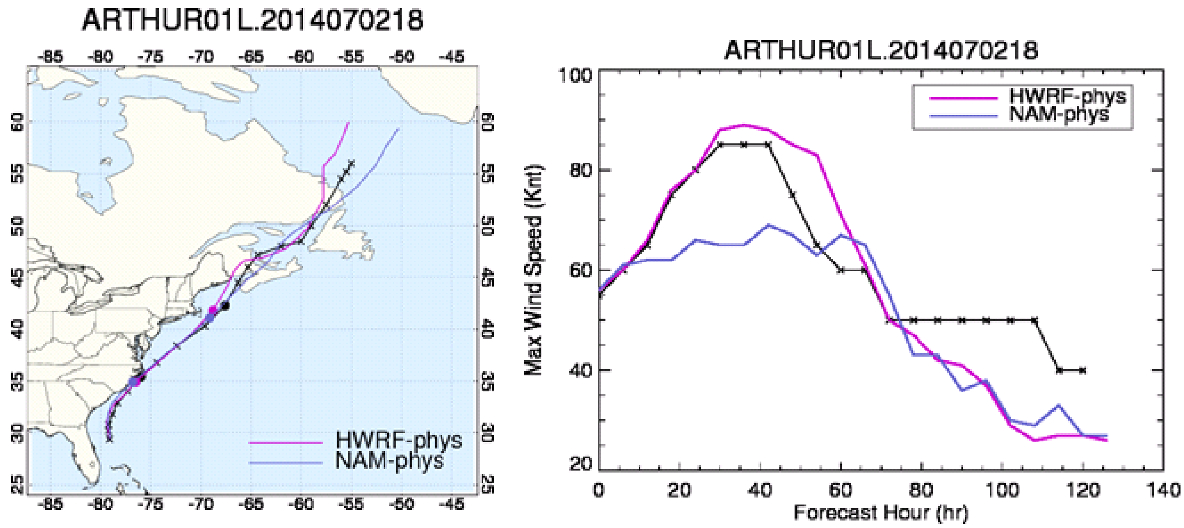


Figure 3.3-3 Forecast comparison of Hurricane Arthur track (left panel) and intensity (right panel) from with HWRF physics (purple) and NMMB with NAM physics (blue). Black lines correspond to the best track data.

The NMMB with HWRF physics experiment showed track, intensity, and landfall characteristics (timing and location) similar to the operational HWRF (not shown) and much closer to the observations compared to NMMB with NAM physics, although the horizontal structure of the storm is comparable between these two experiments. NMMB with NAM physics produced a much weaker hurricane compared to NMMB with HWRF physics.

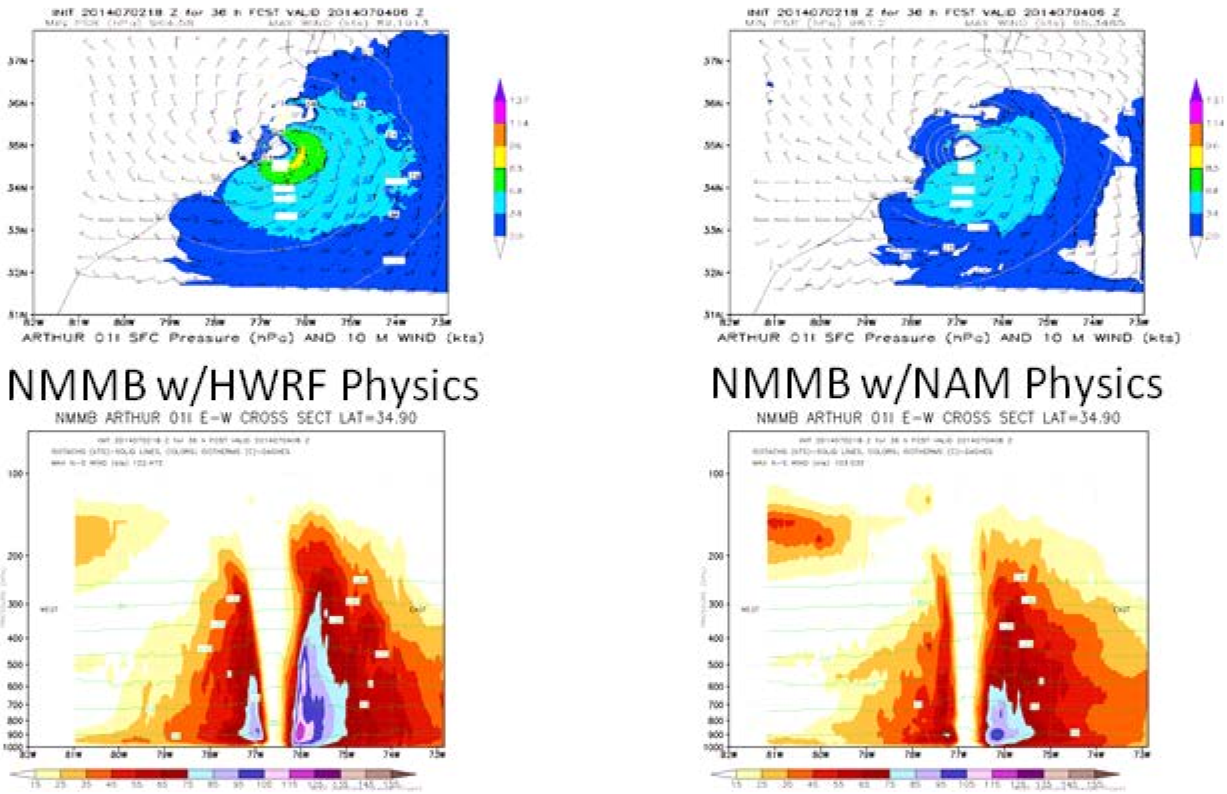


Figure 3.3-3: Horizontal (10m. wind distribution) and vertical structure of Hurricane Arthur at the time of landfall (36-hr forecast) comparing NMMB with HWRF Physics (left panels) and NMMB with NAM physics (right panel).

(3) Major Challenges and Tasks completed

(i) Porting of NMMB/NEMS to Jet: At the start of this sub-project it was quickly realized that the NOAA R&D machine (Zeus) may not be available for dedicated developmental work during the first year. Nevertheless, thanks to the on-going NOAA Hurricane Forecast Improvement Project (HFIP) efforts, additional computing on the order of 1000-2000 processors was provided to HRD/AOML on the HFIP R&D machines (Jet). Further testing and developments of NMMB for hurricane applications required porting the codes from Zeus to the Jet system. A workshop and training on NMMB/NEMS was conducted in Q1 at NCEP that provided about 4 new hires opportunity to learn the NMMB system and NEMS framework. Accelerated porting of NMMB/NEMS to the Jet system was accomplished and all the new developers were trained to conduct the developmental work on both Jet and Zeus during Q1/Q2.

(ii) Global moving nest developments: NMMB is one of the dynamical cores available in the NEMS framework that can be configured in global as well as regional mode. This system is the adopted pathway for operational regional scale applications at NCEP. Extending NMMB for multi-scale hurricane forecast applications provides a seamless pathway towards next generation hurricane forecasting application at NCEP. Preliminary nesting capability, originally based on the HWRF paradigm, was developed at NCEP for mesoscale applications by the start of this project. Nevertheless, significant advancements were made to create a global nested grid framework during Q3 and Q4 of this project. The NMMB model was never used in the past with moving nests in the global configurations. Thus, various challenges needed to be tackled in order to successfully initialize and run the model for the first time ever with multiple moveable nests in a global framework. The first and most critical issue was the initialization of moving nests. Nest motion and 2-way interaction between nest-pairs (e.g. forcing and feedback) require the use of high resolution terrain data sets spanning the entire globe. The NEMS Preprocessing Software (NPS) is the standard operational tool developed by NCEP to initialize the NMMB model and to generate the required high resolution terrain data sets. However, due to a known software infrastructure issue, NPS can only generate these required data sets under regional configurations. We addressed this issue by developing a technique that uses NPS to generate subsets of the required global high resolution terrain data sets and combine them together into the final global terrain data sets. Development of this technique also significantly reduced model initialization time by parallelizing the generation of global high resolution terrain data sets. We then modified the NMMB framework and various nest motion related sub-routines to support the interactions between the global domain and moving nests. Several issues related to invalid floating point values were corrected to prevent model instabilities and eventual failures, allowing for successful simulation of the global NMMB model with multiple moveable nests.

The last major issue involved speeding of the execution of the nest motion algorithm. In the original nest motion scheme, moving nests would read large binary files in their entirety every time they moved. These large binary files contain high-resolution terrain data spanning the entire globe and is required both by (1) model parameterization schemes and (2) to perform hydrostatic adjustment during forcing and feedback processes related to 2-way nest interaction. However, because nests cover only a small region of the globe surrounding a storm, only a very small portion of the actual data is required. This design flaw caused a severe impact on the model runtimes (a 27:9:3 resolution global model with 5 pairs of nests shown in Figure 3.3-1 was impossible to run to generate a 5-day forecast even with 1000 processors within the 8-hr wall clock limit). After an intense analysis of the NMMB nesting code, we identified the primary source of the runtime degradation and worked with EMC to develop a solution to the problem. We developed both a netCDF and a MPI-IO based solution to the problem, allowing only the relevant portion of the high-resolution terrain data files to be read during nest motion. The end result of this work was a tremendous reduction in the cost of nest motion in the global NMMB by significantly reducing the memory requirements for reading the terrain data files during nest motion. This major framework enhancement made it feasible to run the global NMMB within a few hours on Zeus to forecast numerous storms around the globe in 3km high-resolution. Further reduction in run time is expected with increase in resources.

(iii) **HWRF physics:** The success of HWRF in track, intensity and structure forecasting lies not only in its nesting capability but also in its physics package, part of which was advanced at

AOML using hurricane core observations and the hurricane initialization technique that was developed at NCEP. All three hurricane-specific components from HWRF (nesting, physics and vortex initialization) are planned for transition from HWRF to the NMMB/NEMS framework before testing the model for providing tropical cyclone track and intensity forecast guidance in a multi-scale environment. In Q3 and Q4 of 2014, the HWRF physics was seamlessly integrated to the NMMB/NEMS framework (see section 2.2).

4. Some Tests of nesting in the Global NMMB

(i) Importance of 3 km horizontal resolution or better for Hurricane forecasting: Results from the current HIWPP study have already demonstrated that 3km resolution is minimally needed for realistic simulation of hurricane cores. The following results have been generated using NMMB in a global non-hydrostatic, triple nest configuration. In all cases, grid resolution is increased 3x from one nest to the next, yielding a total resolution enhancement of 9x from the global grid to the innermost nest. Figure 3.3-4 shows constant latitude traces of the 10 m wind field of Hurricane Earl 2010 – a relatively large tropical cyclone.

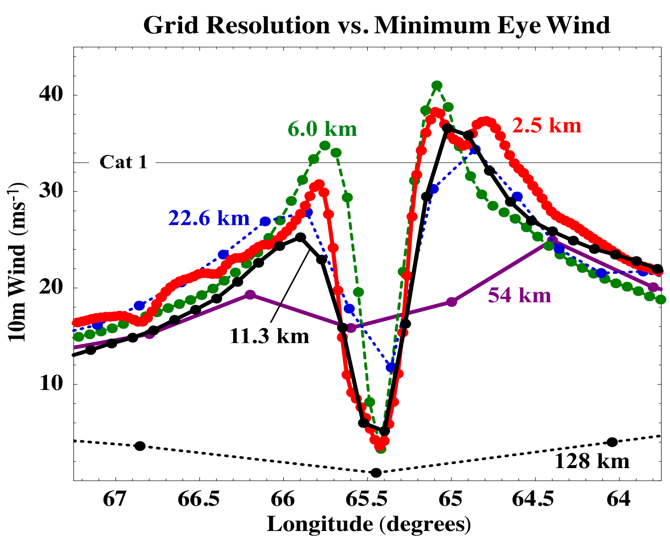


Figure 3.3-4: Effect of mean grid resolution on global simulations of Hurricane Earl at 06 UTC Aug 31 2010. The lowest (global) resolution shown is 128 km vs. the highest (innermost nest) is 2.5 km. Results from four simulations are shown: triple (2-way) nest mean resolutions of 128-43-14.2 km, 54-18.0-6.0 km, and 22.6-7.5-2.5 km; and one double (2-way) nest with mean resolutions of 34-11.3 km. All integrations began with GFS initializations at 18 UTC Aug 26.

All simulations shown in Figure 3.3-4 were collocated to match the 2.5 km result so as to remove the effects of resolution on track and capture the minimum wind in the eye. Figure 3.3-4 also shows that the minimum grid resolution to "approximately resolve" Earl is ~50 km. By "resolve" is meant only that the simulation shows a closed eyewall. By no means is 50 km sufficient for an accurate simulation. As resolution increases, the general trends are for eyewall winds to increase, decreased winds in the eye, and a decrease in the eye diameter. But also note that finer γ-mesoscale eyewall structures – key to forecasting intensity changes – begin to appear *only* in the 2.5 km result. Thus, Figure 3.3-4 suggests that only the 3 km or less simulation has any hope for forecasting intensity changes.

(ii) Importance of the larger scale environment: Figure 3.3-5 provides an example on the importance of resolution for capturing not only the inner core structure but also the multi-scale environment correctly. Again, nesting was employed in the global framework to illustrate this. Figure 3.3-5A shows the near surface wind field simulated in the innermost 2.5 km nested grid. The global model in this case was run at a resolution of 22.6 km (i.e., 22.6-7.7-2.5 km triple nested system). Figure 3.3-5B on the right shows the same wind field simulated by the innermost 14.2 km grid of a 128-43-14.2 km triple nest run – and it is very different. Not only better inner nest resolution (2.5 km) improves structure predictions, but also better resolution employed in the Global domain (22.6 km vs. 128 km) has an impact on the storm location. The 22.6-7.5-2.5 km triply nested system performs better than the 128-43-14.2 km triply nested system**.**

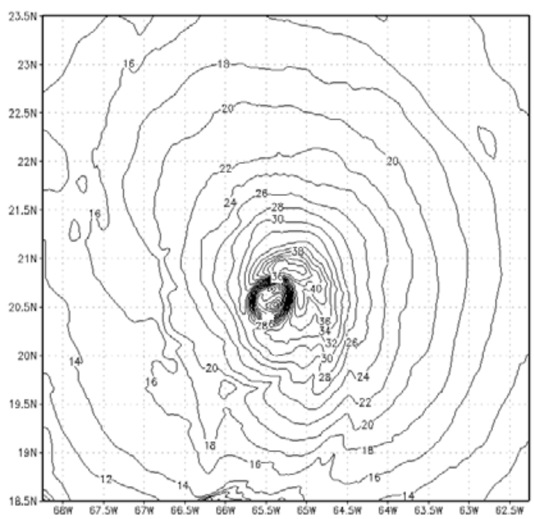


Figure 3.3-5A. 10m wind field of Hurricane Earl 2010 at 06 UTC Aug 31. Result from 2.5 km nest shown in Figure 3.3-2 (22.6-7.5-2.5 km triple nest). 2m wind contours with 46 ms^{-1} maximum.

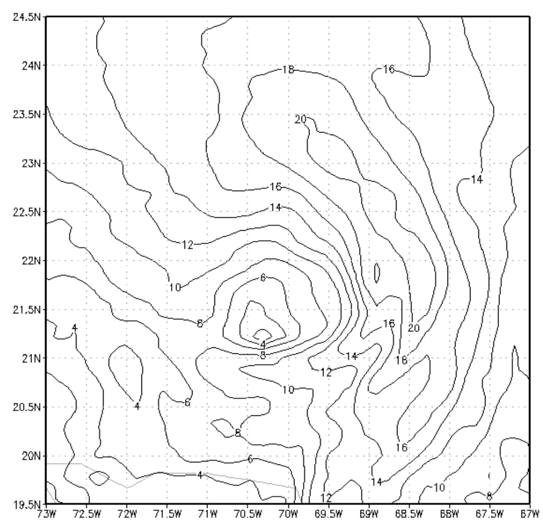


Figure 3.3-5b. 10m wind field of “Tropical Storm” Earl 2010 at 06 UTC Aug 31. Result from 14.2 km nest (128-43-14.2 km triple nest). 2m wind contours with 20 ms^{-1} maximum.

5 Sub-Project: NMME Expansion

Task 3.4

Sub-Project Lead: Jin Huang

As part of HIWPP, the National Multi-Model Ensemble (NMME) is being enhanced to evaluate the prediction capabilities of high-impact weather extremes out to several months, thus ensuring that HIWPP encompasses a seamless suite of extreme weather prediction tools. The main task is broken into 4 sub-tasks:

1. Evaluate NMME-based hurricane seasonal outlook
2. Test real-time NMME-based hurricane season prediction system
3. Assess severe weather environmental factors using NMME data
4. Enhance the current NMME Phase-II data

Sub-task 1: Evaluate and test NMME-based hurricane seasonal outlook

- Project status as of Oct. 2014:
    - Construction and evaluation of the NMME based hybrid dynamical-statistical hurricane season procedures. Initial evaluation procedures with the NMME hindcast suite of April and July initial conditions will commence as soon as a support staff is hired in November 2014.
    - Experimental real-time prediction with the hybrid procedure is planned for the 2015 hurricane season.
    - Explore feasibility of Tropical Cyclone (TC) activity prediction in intraseasonal time scales (weeks 3-4, 30-day mean) with high frequency NMME datasets.

- Deliverables
    - Provide an additional prediction tool for the NOAA Hurricane Season Outlooks with the NMME based prediction procedure.

Figure 3.4-1 shows an example of 30-day mean TC activity prediction during an ATL hurricane season using a hybrid dynamical-statistical model with the Climate Forecast System, version 2 (CFSv2) seasonal prediction.

Sub-task 2: Test real-time NMME-based hurricane season prediction system

This task will follow after the completion of sub-task 1.

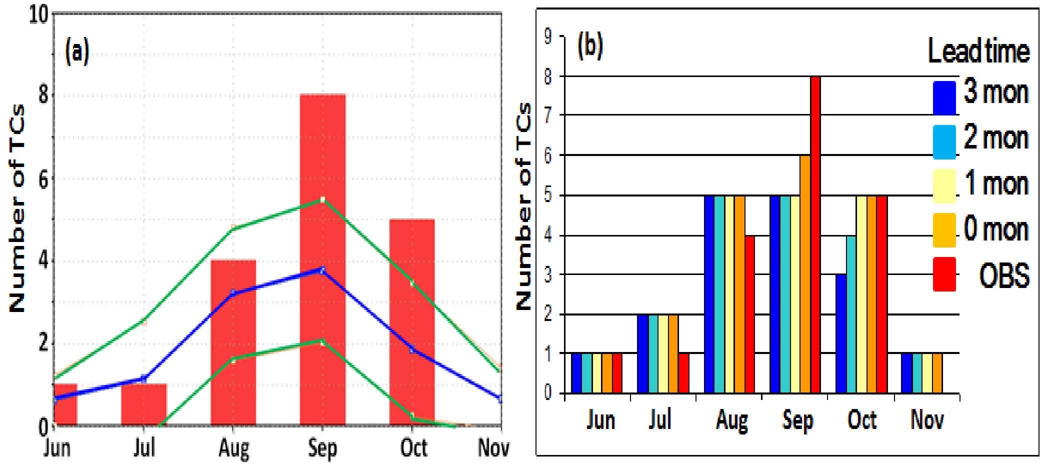


Figure 3.4-1 Monthly distribution of tropical cyclones in the 2010 Atlantic hurricane season (a) and forecasts of monthly tropical cyclones for the 2010 hurricane season (b) using the dynamical–statistical model (Wang et al. 2009) with lead time from 3 months to 0 month. Blue line in (a) is the monthly tropical cyclone climatology (1981–2009) and green lines are +/– one-standard-deviation departure from the climatology.

Sub-task 3: Assess Severe Weather Environmental Factors Using NMME Data

- Made progress in terms of comparing NCAR/CCSM4 and CFSv2 CAPE (Convective Available Potential Energy) with NARR data (see Figure 3.4-2)

- Established collaborations with the NCEP/Storm Prediction Center (SPC) by leveraging a new FY14 CTB funded project (PIs: Mike Tippett and Greg Carbin)
    - o Worked with Greg Carbin (SPC) and Mike Tippett, who are the PIs of the newly FY14 funded MAPP-CTB project on assessment of CFS prediction of US severe weather activity
    - o Set up a wiki page for the NMME Expansion Project to share results with the MAPP-CTB project. http://extremew.wikispaces.com/CAPE
    - o Started looking at other indices and teleconnections for severe weather over North America - in collaboration with Tippett.

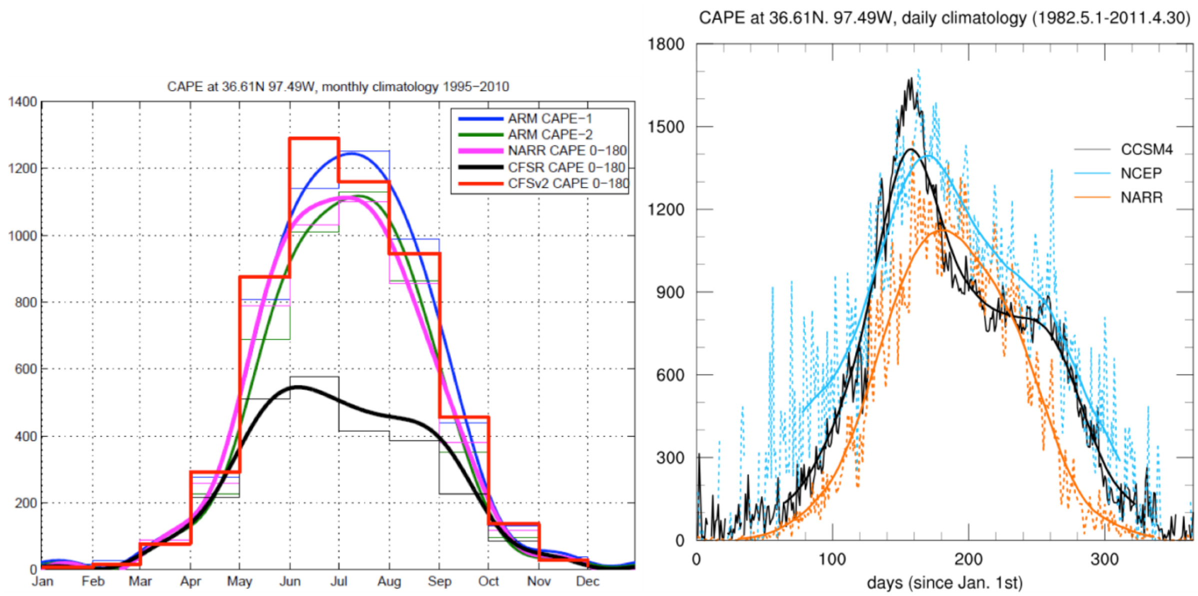


Figure 3.4-2 CAPEs (CCSM4, NARR and NCEP) a) Monthly Climatology and b) Daily Climatology (Solid lines: 30-day running-average; Noisy lines : raw-daily data).

Sub-task 4: Update on the Phase-II data archive including the high frequency data for HIWPP

Substantial progress has been made toward publishing data to the NCAR Gateway. In summary, it is expected that all monthly and daily data will be available for five models by 01 January 2015, with the remaining two models coming in by 01 March 2015.

- **GFDL_FLORb**: all data has been published.
- **CanCM3 and 4**: all data is expected to be published by 15 Oct.
- **NASA-GEOS5**: 10% expected to be published by 15 Oct., 100% on or before 01 Jan 2015.
- **NCAR-CCSM4**: 25% by 31 Oct., 100% on or before 01 Jan 2015.
- **CFSv2** daily and 6hr data will be gradually published over the next 5 months, expected 100% by 15 Mar 2015.
- **NCAR CESM** likely to be published by 15 Mar 2015.
- **Status/plan for the enhanced Phase-II data**
    - **Data Products**
        - 6-hourly : Mean sea level pressure, surface temperature (SST and land), precipitation, 3D temperature and winds (both u and v)
        - 3-hourly: 6-hourly fields above including Surface winds (wave models
    - **Data Archive Delivery Plan**
        - RSMAS CCSM4 3-hr: 25%, Dec 1, 2014, 100% Mar, 2015.
        - NCEP CFSV2 6-hr: 100% March, 2015
- Address of the **NCAR Gateway**: https://www.earthsystemgrid.org/search.html?Project=NMME
- Updated list of **Phase-II products**: www.cpc.ncep.noaa.gov/products/ctb/nmme/NMME-PhaseII-DataPlan-27May.pdf

References:

Wang, H., J. Schemm, A. Kumar, W. Wang, L. Long, M. Chelliah, G. Bell and P. Peng, 2009: A Statistical Forecast Model for Atlantic Seasonal Hurricane Activity Based on the NCEP Dynamical Seasonal Forecast. *J. Climate*, **22**, 4481-4500.

6 Sub-Project: Test Program

Sub-Project Lead: Bonny Strong

6.1 Introduction

The Test Program had a very active start in HIWPP. As the Test Program supports analysis and evaluation of the outcomes from the other sub-projects, many of the Test Program deliverables were required early in the project. With the delayed release of project funds, schedules were compressed, especially with regard to major hardware purchases that had to be completed in FY14. The Test Program sub-project consists of four tasks:

- Statistical Post-Processing
- Visualization and analysis via NOAA Earth Information System (NEIS)
- Verification
- Real-time IT Operations

Each of these tasks operates on the output of the HIWPP modeling tasks to provide additional analysis, evaluation, and distribution of the model data. Each is fairly independent of the others, but all depend on new hardware infrastructure purchased as part of the HIWPP project.

Major software development was completed on schedule by the Statistical Post-Processing and NEIS tasks, and both tasks have produced systems which will support analyzing and visualizing the real-time model data expected to be available in Q1 of FY15. The Verification task has built a strong connection between NCEP and ESRL verification teams, and has completed an evaluation of existing and new features which should be included in a combined advanced verification system. Development on the new MySQL-based system has begun. The Real-Time Operations task has been responsible for the requirements, purchase, and installation of a major new advanced storage system which will support data flow for all the Test Program tasks.

The earliest output from combined efforts of all four task leads and team members was a Systems Engineering document for the HIWPP System. This 38-page document defined the requirements and design of the system, along with data specifications, configuration management, support, and monitoring plans. This document is kept updated as the definitive technical specification of the HIWPP System as it will be delivered at the end of the project.

As soon as project funds became available, action was taken to submit purchase requirements for the major hardware components underpinning the HIWPP infrastructure for model comparison and evaluation. The major components of this infrastructure were:

- A 150-TB storage system to collect model output and make it available for visualization, verification, and post-processing,
- High-speed processing servers to support visualization and analysis,
- Virtualization servers for visualization, verification, and data distribution processes,
- Network switching equipment to provide necessary interconnectivity.

Delays were encountered with purchasing, but interim solutions were found that permitted the Test Program staff to continue development and testing. Hardware was delivered during the June – July timeframe. Following installation, serious performance issues were encountered with the storage hardware, which required intensive efforts from the technical support staff, working with the hardware vendors, to identify and correct. All hardware installation was completed and all issues resolved by October 7, 2014. The project would like to acknowledge the efforts of the ESRL/GSD technical staff that were able to resolve complex, unprecedented issues with the hardware in order to support the HIWPP project schedules.

Though funding was delayed and hardware was not available in the expected timeframe, development for the four tasks within the Test Program still proceeded very close to planned schedules and deliverables for the first year of the project were completed within the constraints of available model data.

6.2 Task 3.5.1 Statistical Post-Processing

Task Lead: Isidora Jankov

The first year of the HIWPP statistical post processing included analysis of a sample data set including two models, GFS and FIM, of December 2013 thru February 2014 of five variables of interest: 2m Temperature, Geopotential Height at 500mb, 10m Wind, and accumulated precipitation for forecasts from 12 hours to 192 hours. This sample set was used to develop the methods that are incorporated into a production post processing code that allows flexibility in the number of models, the length of training data, and the source of analysis or observations. The code was successfully developed by the end of the first fiscal year of the HIWPP program and is currently running on a 12-hour schedule using the FIM and GFS real time outputs available and is ready for the inclusion of the NAVGEM model. In analyzing methods that may be used for the first implementation of the post processing, GFS analysis was used as the 'truth' for estimating the errors in each model for all variables except precipitation. For precipitation CMORPH analysis was used. The code that has been developed is designed for immediate inclusion of other sources of 'truth'.

In the initial phase of analyzing the sample data, we set out to determine how much training data is needed, assuming the recent past skill is the metric for the current forecast skill. In this study of the length of the training needed, it was determined that 25-30 days was where the benefit of recent data plateaued and therefore the continued development focused on using 30 days of the most recent information to train the post processing.

The first step of the post processing was to remove the bias, or the mean error in the statistical training period, 30 days. After the bias was removed from the models, the remaining error was used to determine how to weight the models to yield a single result that has greater skill than an arithmetic mean. Using the model forecasts with bias removed at each point on the global grid, the weight of each model at each grid point was defined as inversely proportional to its Mean Absolute Error (MAE) over the training period.

In addition to the weighting, the sample set was analyzed for using regression to improve the forecasts. The experiment in the sample set determined if a constant of proportionality between a model and the truth existed and determined the amplitude of this constant for each point on the grid. Using regression coefficients was determined to reduce error for longer forecasts, greater than ~100 hours, but verification is needed because when inspected, the mean regression coefficients were less than one and decreasing with increasing forecast length, suggesting that the regressed result was being pushed toward climatology.

In addition to producing a statistical forecast with greater skill than the arithmetic mean of the models, we created a probability distribution around the weighted mean result for all variables except precipitation. After analyzing the histogram distributions of a great number of points on the global grid, we determined that the distributions appeared normal and we have therefore chosen to represent the probability distributions by a single metric, the standard deviation of the error in the weighted hindcasts. The 'weighted hindcasts' are the forecasts in the training data weighted with the current forecast weights (Figure 3.5.1-1). For precipitation, the probability is characterized by the probability of exceeding 1, 5, and 10 mm accumulated precipitation for each point on the grid defined by an exponential distribution where the exponent is defined by the reciprocal of the quantitative precipitation forecast, or in this case, the weighted mean precipitation forecast.

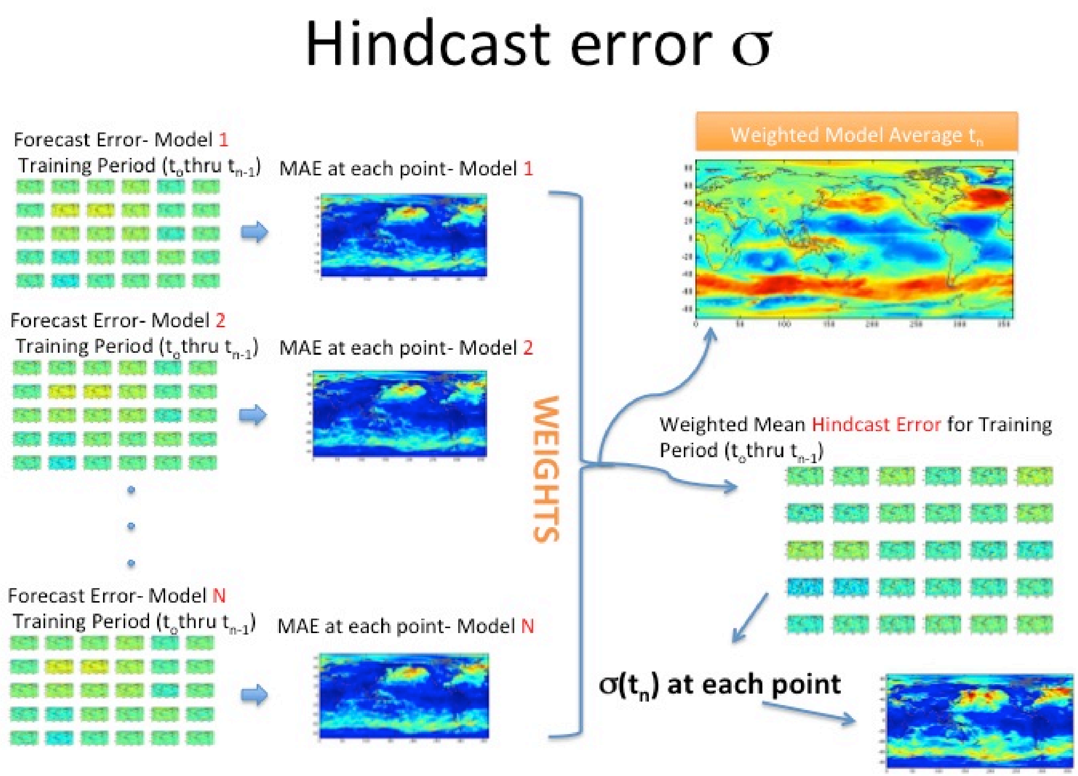


Figure 3.5.1-1 An illustration of hindcast error calculation and its use for distribution estimation at each grid point.

In summary, the first year milestone of delivering a real-time system for producing the best estimate and associated probability and distribution for surface temperature, wind, precipitation and 500mb geopotential height at each grid point on the globe has been accomplished. For baseline, arithmetic mean has been used.

The real time system is highly modular allowing inclusion of various models, analyses, observations and post-processing methods as well as expanding the set of variables processed. The output is available on the NEIS system (Figure 3.5.1-2).

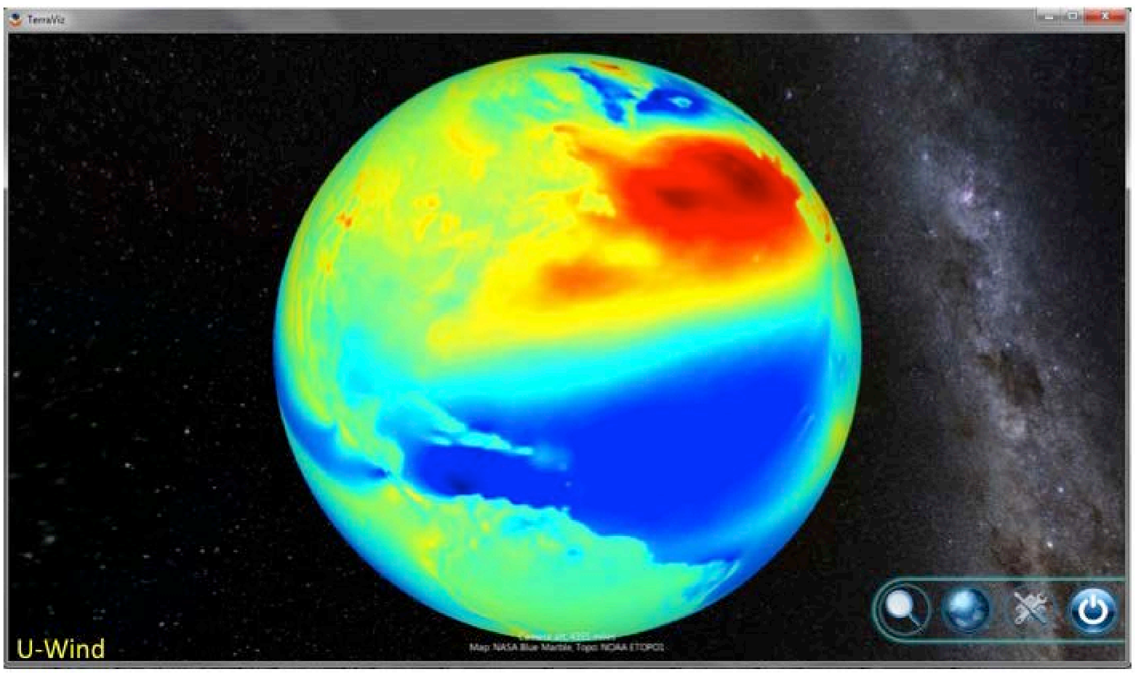


Figure 3.5.1-2 An example of NEIS visualization for surface U wind component weighted-mean calculated for the sample data used for the system development.

6.3 Task 3.5.2 Visualization and Analysis via NEIS

Task Lead: Jebb Stewart

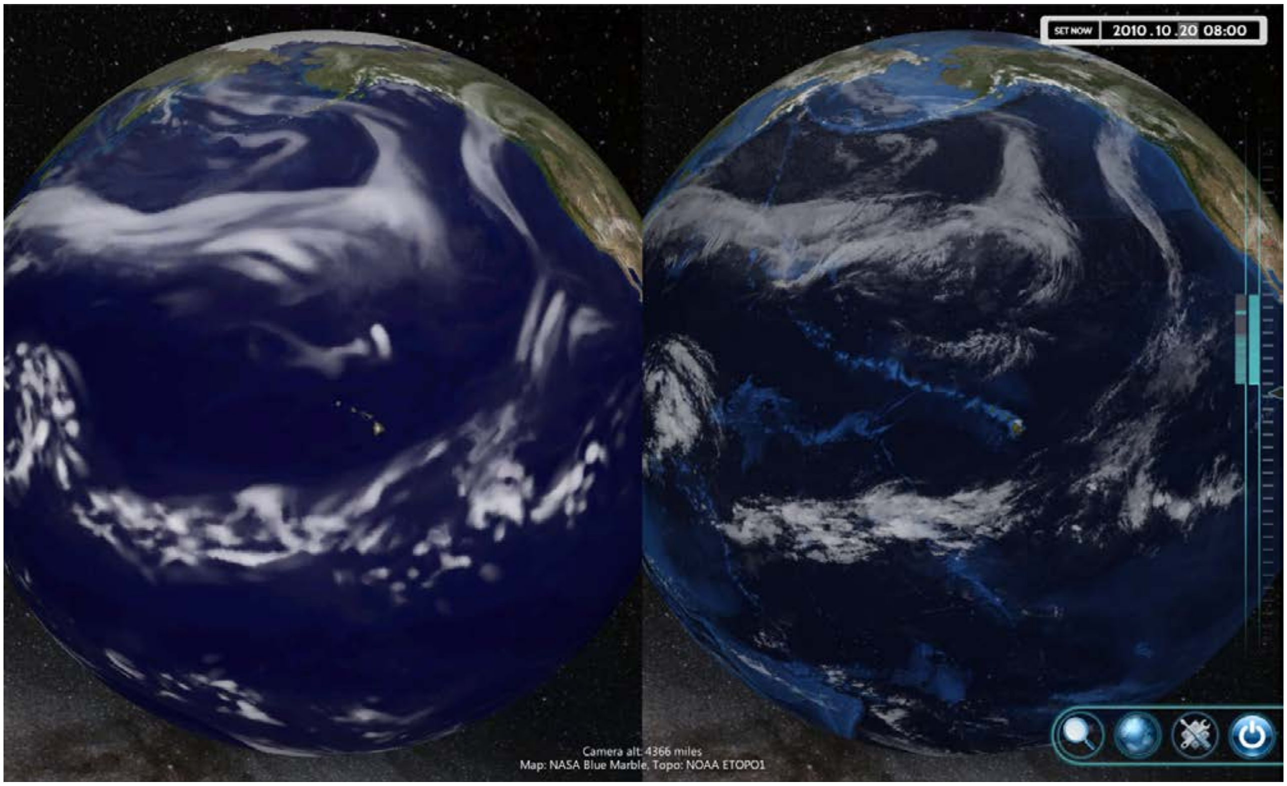
During the first year of HIWPP, this task built upon a prototype NEIS system, adding major new capabilities and architecting for very ambitious performance targets.

FY14 Overview

For the Fiscal Year ending 2014, task 3.5.2 successfully met all milestones outlined in the HIWPP Project Plan. NEIS successfully expanded the prototype NEIS system adding capabilities to help others visualize, interact, and integrate HIWPP data with other geolocated environmental data. Through FY14 the following improvements were made:

- Developed and implemented architecture for high performance real-time research data ingest system for new high resolution gridded model data, point data. These systems provide existing global operational models and global satellite observations, as well as available experimental HIWPP data to users. All data is made available for at least the previous 24 hours, often up to 48 hours.
- Created high performance service layer allowing fast access, visualization, and integration capabilities to real-time research data
- Created initial high performance processing capability to providing analytic capabilities allowing users to run analytics or algorithms remotely only sending relevant data for display
- Integrated Task 3.5.1 Statistical Post Processing data.
- Updated visualization capability (TerraViz) to provide high performance tools for model evaluation and comparison.
- Developed, Side by Side or Multi sphere display allowing users to visually compare forecasts in real-time. The image below provides an example of the side by side capability with forecasted simulated IR imagery on left, with actual observed global composite IR imagery on right.

Through various demonstrations and presentations the NEIS team received encouraging feedback on direction of development advances and received great interest from various users who explicitly stated interest in participating in the HIWPP Open Data Initiative.



3.5.2- 1 Image created using NEIS visualization tool comparing cloud images simulated from FIM model output to actual satellite images of tropical cyclone Megi of October 18, 2010

Challenges

Throughout the year, task 3.5.2 encountered several challenges that impacted the schedule and deliverables. Towards the end of the third quarter, the NEIS team lost a key software engineer. This position was filled promptly within 1.5 months. Time was lost both because of lack of coverage during the interview and hiring process, and the on-boarding required to bring the new software engineer up to speed.

Additionally, delays from other dependent HIWPP tasks resulted in challenges in having proper data and hardware available for testing and implementation of NEIS concepts. NEIS team was able to move forward with test with example data and prototype hardware, however the final impacts may not be known until other tasks meet their deliverables.

A couple of key challenges remain which currently impact task 3.5.2. Currently, no enhanced hydrostatic data is available for the GFS and NAVGEM as well as Hydrostatic Ensemble data from task 3.1. Additionally task 3.5.4 is currently working through hardware installation problems which impact the public testing and access to NEIS capabilities and services. These issues are known and are being worked through with HIWPP management.

Next Steps and Future Plans

In the next month (Oct-2014), a final development report will be delivered to HIWPP partners. Additionally the NEIS visualization client (TerraViz) will be delivered to HIWPP partners once externally accessible hardware is available and the associated challenges from task 3.5.4 have been resolved. Each following quarter, a new release of NEIS visualization software with updated capabilities will be made available to the HIWPP team.

Through the remainder of the fiscal year, the following capabilities will be added:

- Add new data to help the evaluation of HIWPP forecast models including verification data from task 3.5.3.
- Enhance processing capabilities, expanding available analytics tools.
- Add new volumetric capabilities to NEIS framework allowing user to generate cross sections and other access to full volume of gridded forecast data.

Risks

NEIS is on track and the current system has capabilities to provide HIWPP Hydrostatic and limited non-hydrostatic data. With real-time data flow from all hydrostatic models not available to date, NEIS has been tested with mock and simulated data. Through these tests we believe NEIS will be able to handle full data flow and meet our deliverable schedule. However, once real-time data is flowing, system may require unforeseen changes to handle full data volume. If changes are required, this will impact deliverable schedule.

6.4 Task 3.5.3 Verification

Task Lead: Stephen Weygandt

The goals of the HIWPP verification sub-team are to provide reliable, insightful, robust verification of the HIWPP real data hydrostatic and non-hydrostatic model runs, including both retrospective and real-time model runs. These results are to be stored in a statistical database, with interactive display capabilities. The verification work is a collaborative effort including scientists from ESRL GSD and NCEP EMC, with a longer-term goal of creating a verification system to serve NOAA operational model developers that captures the best attributes of existing systems including:

-- inclusion of a base-line set of verification scores (anomaly correlation, upper-air verification, surface verification), as well as precipitation verification, ensemble verification, and composite “scorecard” verification

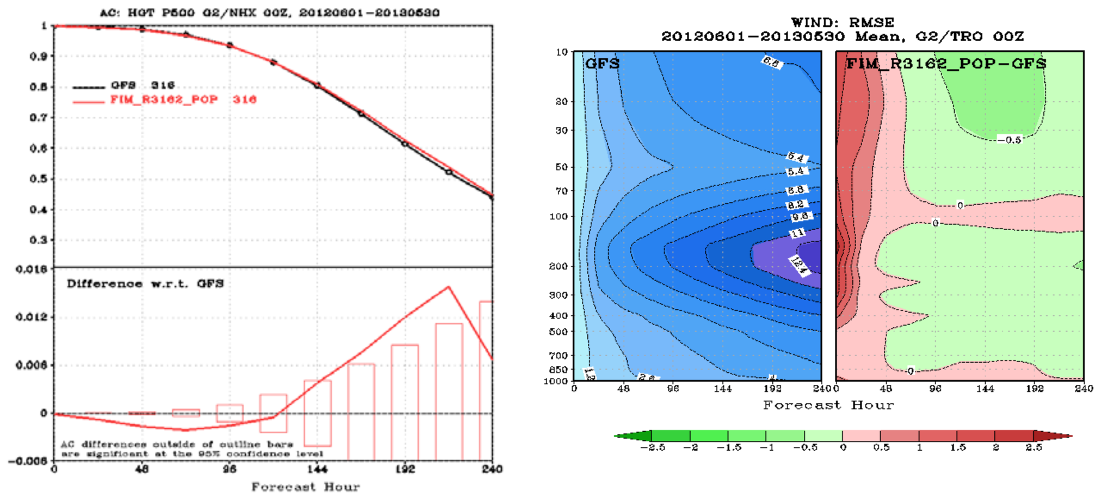
-- inclusion of capabilities to generate both fixed sets of verification scores and to allow interactive selection of different verification stratifications

-- ability to provide quick feedback for both retrospective and real-time experiments

and adding advanced verification capabilities, including station-based global verification of sensible weather elements including surface temperature, dew point, and wind, and precipitation, and comparison of multiple forecast-based error distribution plots for different models and regions.

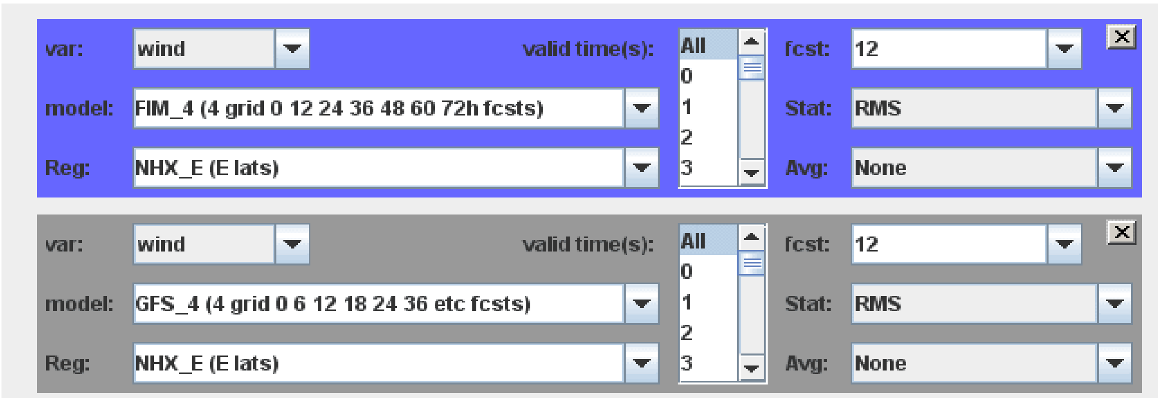
In the first year, the verification sub-team made good progress toward these goals, meeting most of the specific milestones and laying the groundwork for a successful second year. Early in the year, efforts focused on two key tasks: 1) working with GSD IT specialists to put in place computer systems (virtual machines) to house dedicated HIWPP verification database and web-display systems, 2) working with EMC scientists to build a shared understanding of verification requirements for HIWPP and future overall NOAA operational model development. The computer systems were rapidly put in place and successfully tested, satisfying one of the early milestones. In addition, EMC scientists were able to access the system, allowing for a shared work space. Work toward this second goal included a series of meetings to present aspects of both the current EMC ESRL/GSD verification systems and exchange of codes and running of significant portions of the EMC verification code by ESRL GSD scientists. From these meetings, a shared vision of the needed attributes for the verification system emerged, including the need for database storage of statistical results to allow interactive examination of the data. Additional discussions with Navy personnel indicated similar priorities in their verification work and collaboration has begun with them as well.

GSD work then focused on testing of the initial verification system (composed of elements from the EMC Verification Statistics Data Base (VSDB) system), and developmental work toward adding the more advanced capabilities. Some staffing issues at GSD (loss of a verification scientist to a position in the private sector and extended medical absences of two other scientists) delayed the beginning of this work, but a talented young scientist was brought on board in Aug. 2014, satisfying another milestone, and work is proceeding well. In fulfillment of another year 1 milestone, ESRL GSD verification scientists have been running the main components of the EMC verification, as part of the initial HIWPP verification system. Because of delays in the completion of the FIM and NAVGEM retrospective runs, we have initially been applying this system to FIM and GFS real-time and retrospective runs. Figure 3.5.3-1 shows a sample output from different components of the EMC verification system. This system stores results in ASCII “VSDB” files generates a fixed set of “static” statistical comparison images. As part of the work for the advanced HIWPP verification system, these capabilities will be integrated into the HIWPP database verification system.



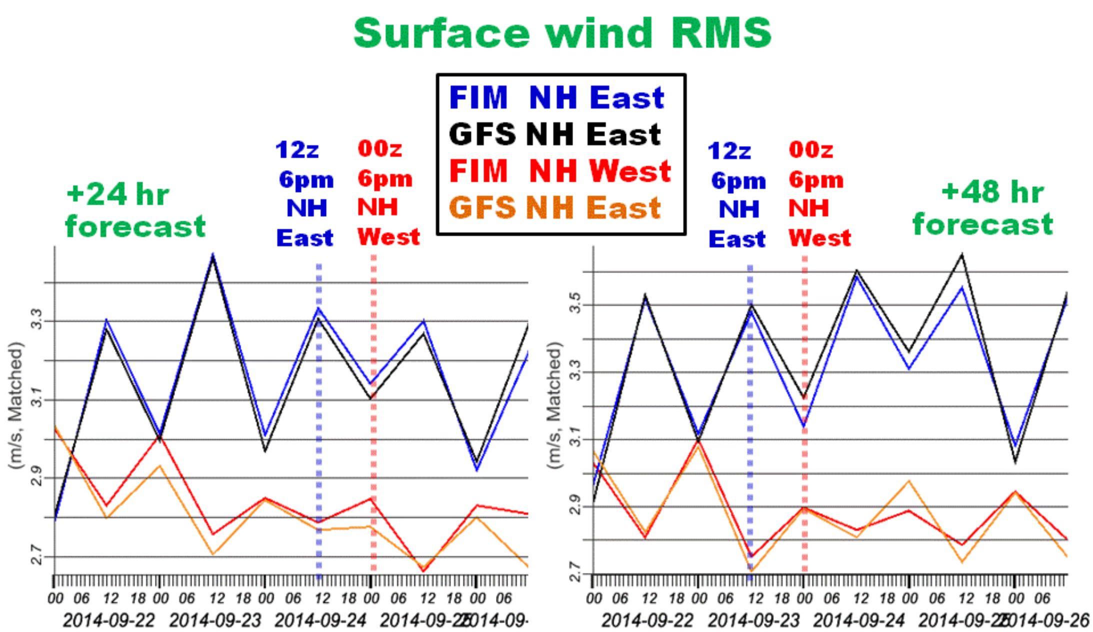
3.5.3-1 Sample verification graphics generated using the EMC verification package run by ESRL GSD, as part of the initial HIWPP verification capability. Shown on left is a comparison of GFS and FIM Northern Hemisphere 500 hPa anomaly correlation coefficients. Shown on right is a height vs. forecast length plot of GFS and FIM – GFS RMS wind errors for the tropics (-20 to +20 deg. lat.)

More recent verification work has focused on expanding the capabilities of the GSD database verification system to include global station-based surface (METAR) verification of sensible weather elements. This task has included work to ingest the METARs into the database and compute the difference statistics and update the web interface. Preliminary testing of this new capability has been completed and suggests the system is working correctly. Fig 3.5.3-2 is a screen capture of the web interface for the interactive verification statistical selection tool. Shown are the various selectable parameters for the data query [variable, model, region, valid time, forecast length, verification statistic, and averaging period].



3.5.3-2 Screen capture of web interface for the interactive verification statistical selection tool, showing query for comparison of FIM and GFS surface wind RMS for Northern Hemisphere East.

Fig. 3.5.3-3 shows sample time-series (successive matched model forecasts) plots of FIM and GFS forecast surface wind RMS errors for two different regions (NH East and West) and two different forecast lengths (+24 h and +48h) with some additional annotation.

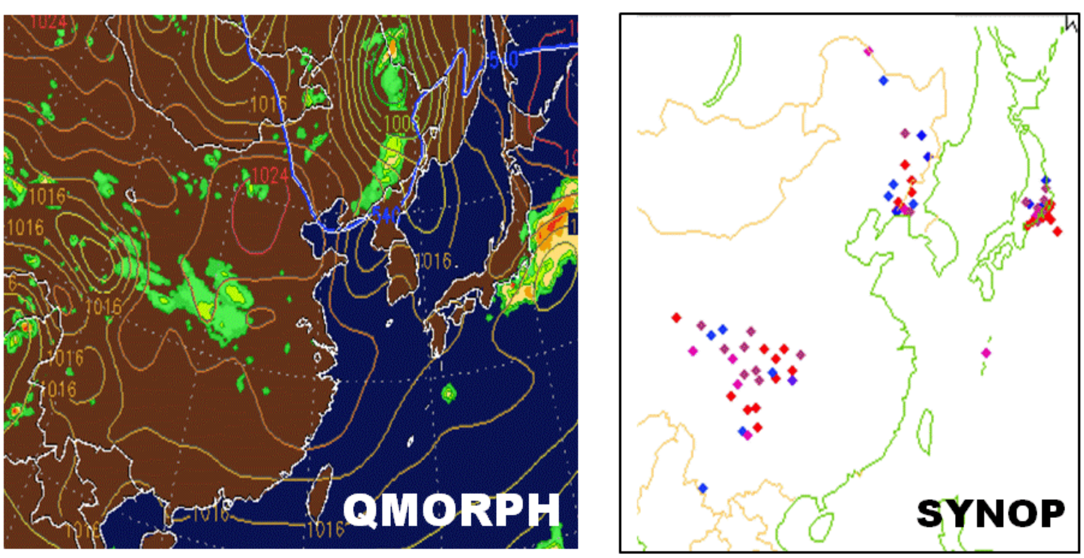


3.5.3-3 Time series of surface wind RMS errors for two different models (FIM and GFS), two different regions (Northern Hemisphere East and Northern Hemisphere West) and two different forecast lengths. See text for additional details.

In addition to the comparison between the two different models for the two different forecast lengths, other patterns can be seen in the graphic. In particular, the saw tooth pattern of wind error maximum and minimum for different times of the day is consistent with expectation for the different Northern Hemisphere longitude regions. Given that surface wind RMS errors are likely to be larger in the afternoon than the morning, and that for the eastern hemisphere afternoon is closer to 12z (and the converse for the western hemisphere), we would expect the documented error pattern. Note also that in addition to the “time series” mode shown in Figure 3.5.3-3, plots can also be generated as a function of forecast length (die-off plots), valid time of day (diurnal cycle plots), and vertical profiles (for upper-air verification).

In addition to the work to add a global station-based surface verification for wind, temperature, and dew point; progress has been made toward adding a surface station-based precipitation verification capability. The key observation dataset for this work is the global SYNOP network, and GSD IT personnel (Leslie Elwy) developed and implemented a decoder for SYNOP data and is generating SYNOP observation in real-time. These data have then been ingesting into an ESRL data base and integrative display system. This database and display allows perusal of the data and is a prelude to calculation and display of precipitation verification. Figure 3.5.3-4 shows a sample comparison of a display of non-zero SYNOP 6h precipitation reports (accumulation amount legend omitted) with a QMORPH 6-h precipitation analysis (courtesy Mike Fiorino, accumulation amount legend omitted). Examination of the two plots reveals a good qualitative agreement.

+6h accumulated precipitation ending 18z 15 Oct.



3.5.3-4 Qualitative comparison of QMORPH satellite based 6-h accumulated precipitation with SYNOP station reports of precipitation ending at 18z 15 Oct. 2014.

Work is ongoing, and will continue on year 2, to complete the precipitation verification module, and add ensemble and score card verification. Work to verify the hydrostatic retrospective runs has been delayed due to delays in the completion of the FIM and NAVGEM retrospective runs, but is expected to begin shortly. File from the T1534 GFS retrospective runs have been accessed and verification of the retrospective run is ongoing.

6.5 Task 3.5.4 Real-time IT Operations

Task Lead: Bonny Strong

The Real-time IT Operations task incorporates several sub-tasks, including:

1. Collect model data into a central location, where it is available for post-processing, visualization, and verification
2. Acquire additional data needed for verification and visualization
3. Distribute model data to public data users as part of the HIWPP Open Data Initiative
4. Provide tools and infrastructure to support the Open Data Initiative
5. Provide and support a community portal for communication and collaboration of all HIWPP project members
6. Provide documentation, monitoring, and support for real-time data operations.

<u>New hardware and infrastructure:</u>

The most critical component of this task for delivery in year one was the new storage system, without which model data could not be collected in a single location for post-processing, visualization, verification, and distribution. The purchase of the storage hardware was impacted by the delayed release of funds. Once delivered and installed, serious performance issues were encountered, along with problems with high-availability failover operations.

In order to address the performance issues of the new storage system, the storage vendor was contacted and agreed to dedicate technical staff to trouble-shooting and three top-level technical staff members from ESRL/GSD were dedicated to the task. From this intensive effort, the technical staff was able to identify an operating-system-level bug which was encountered only under the heavy load presented by the advanced visualization technology built for HIWPP. Once identified, the bug was quickly resolved, and the storage system became stable and well-performing with high-availability failover functioning correctly.

<u>Data flow and distribution:</u>

In order to identify requirements for the data collection and distribution system, an analysis of the data flow for all HIWPP data was completed with results shown in Figure 3.5.4-1.

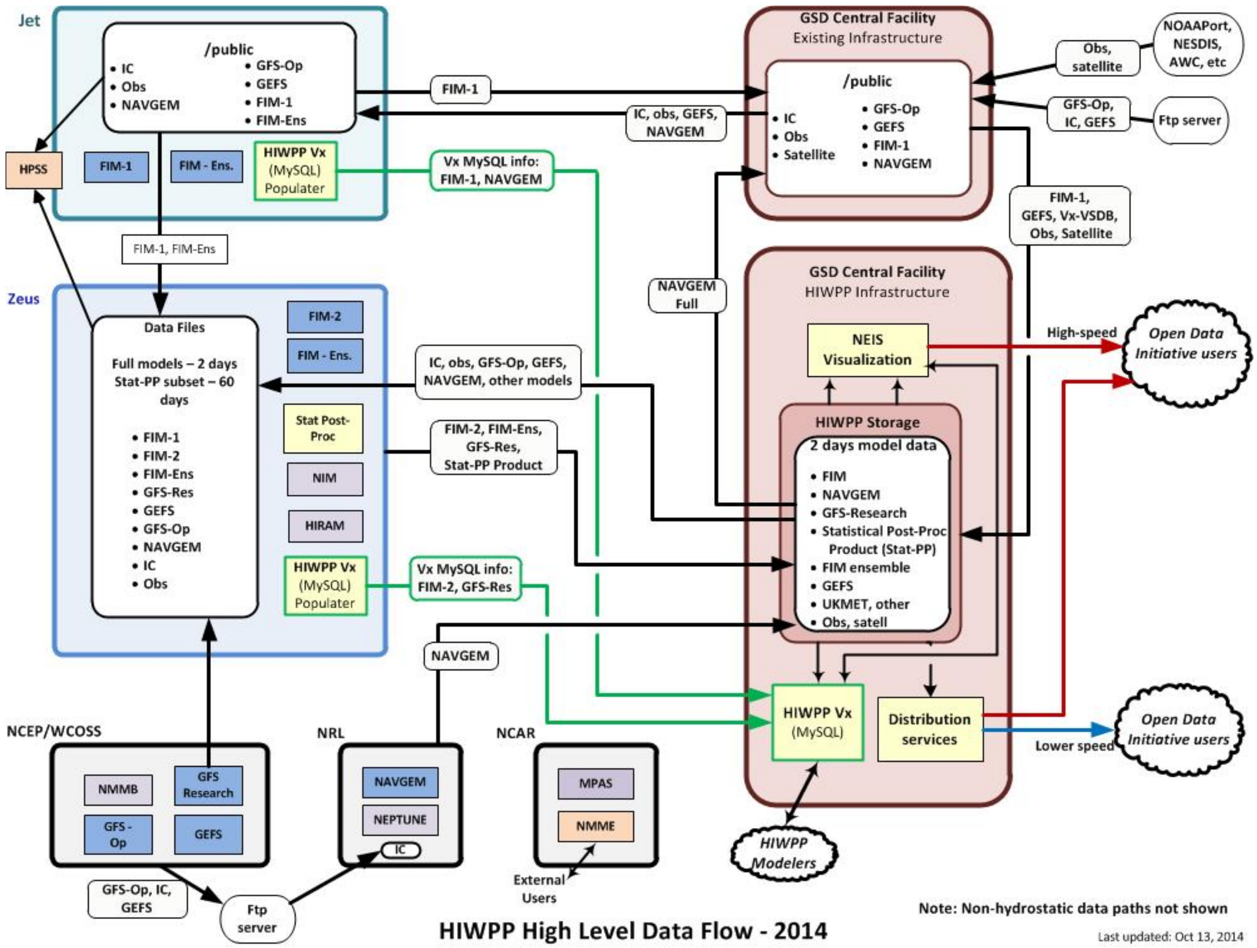


Figure 3.5.4- 1 HIWPP Data Flow

Available technologies to support the data distribution system were evaluated. Maximum bandwidth to receive the complete output of all HIWPP hydrostatic model data was estimated, assuming the maximum of 2 models each for FIM, GFS, and NAVGEM (running different model physics or different data assimilation systems), with output at 1/8 degree resolution, hourly for days 1-7 and 6-hourly for days 8-14. Bandwidth to receive the maximum estimated output data stream was computed to be 65 Mbits/sec average rate, with 130 Mbits/sec peak rates.

In order to support users who do not have the network capacity to receive the full data sets, a distribution mechanism that allowed receiving a selected subset of data was considered essential. From this requirement, it was decided that the best technology for data distribution would be a THREDDS service, as supported by UCAR Unidata. A decision was made not to support direct ftp access due to difficulties with user authentication. Access via Gridftp was considered, but concerns were raised that it was not possible to limit the number of threads used by any user, thus not allowing any control over bandwidth utilized by individual users.

For user authentication, it was desirable to find a mechanism that did not require data users to have a NOAA user id, and would not incur any ongoing cost. Investigation found that an Earth System Grid

Federation (ESGF) (see https://www.earthsystemgrid.org/about/overview.htm) OpenID service was already being provided within ESRL by the NOAA Environmental Software Infrastructure and Interoperability (NESII) group, and could be leveraged to provide authentication for HIWPP. This coupled nicely with the CoG system selected to provide the community portal, described below, which is also using the ESGF OpenID service for authentication.

A significant bottleneck in the data flow was identified as transfers between the Zeus HPC system in Fairmont, WV and the GSD facilities in Boulder, CO. A pair of computer servers were purchased and installed to serve as a data transfer gateway for this link, with network tuning optimized for real-time model data transfers.

The Real-time IT Operations task also needed to provide a community portal for communication and collaboration of all HIWPP project members. The Earth System CoG (http://earthsystemcog.org/projects/cog/) was chosen as the platform for this portal. CoG is a software environment that supports community development in multi-project, distributed organizations. Many HIWPP project members were familiar with CoG from the 2012 Dynamical Core Model Intercomparison Project (DCMIP). Both public and private HIWPP projects were created within CoG, and sub-projects were created for each of the 5 HIWPP sub-projects. This portal has provided a platform to share information between project members, such as meeting information or definitions of test cases. It will also provide a platform for interaction with the general weather community within the Open Data Initiative. A screenshot from the page for the non-hydrostatic idealized test cases is shown in Figure 3.5.4-2.

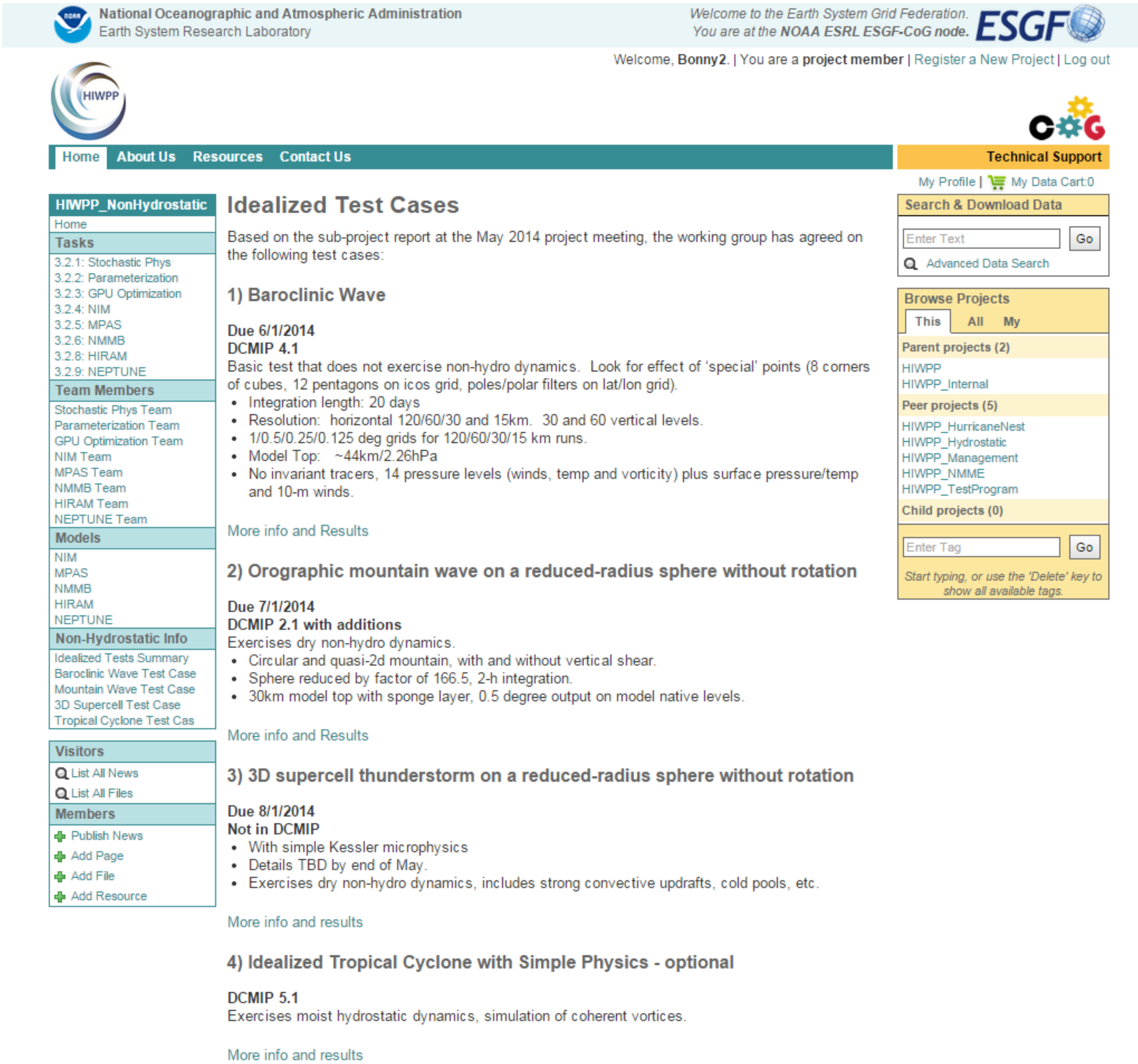


Figure 3.5.4-2 CoG page for Non-hydrostatic Idealized Test Case Summary

<u>Open Data Initiative:</u>

One goal of the HIWPP project is to have an open process that allows interested parties from the public, private, and academic sectors to access HIWPP data and to engage in the research process. It has fallen within the scope of the Real-time IT Operations task to plan how this goal will be implemented. During this first year of the project, a policy has been developed and reviewed with both NOAA legal and policy personnel and within the HIWPP project. Components of the Open Data Initiative include:

- Announcing the opportunity to the public

- Providing a mechanism for users to register to receive model data and/or NEIS visualization tools
- Identifying risks and mitigation strategies if expected demand for data exceeds available capacity
- Designing a mechanism for users to provide feedback about model performance
- Designing a test plan and rollout process

At this stage of the project, plans and designs for the above components have been completed, and all will be implemented during the first quarter of FY15. Testing is planned for early in Q1 of FY15, with the system ready to go live by the end of Q1.

7 Summary

In summary, the HIWPP project has had significant achievements for its first year, including:

1. Hydrostatic Global Models: Development of GFS, FIM, and NAVGEM to run at higher spatial and time resolutions, close to readiness to run in real-time operational or real-time research mode.
2. Non-hydrostatic Global Models: Completion of common set of idealized test cases and report summarizing the results; coordination with Next Generation Global Prediction System (NGGPS) project and Advanced Computing Evaluation Committee (AVEC) which will build upon HIWPP work.
3. Moving Hurricane Nest: Completed a Proof of concept of Global tropical cyclone model with multiple moveable nests placed around all tropical systems in the world, and implemented and tested all TC specific physics schemes from HWRF in the NMMB.
4. NMME Expansion: Progress toward an archive of enhanced NMME data for public access and initial construction and evaluation of the NMME based hybrid dynamical-statistical hurricane season procedures.
5. Test Program: Purchase and installation of major new hardware resources; development of a production-ready statistical post-processing product; release of version 1 of the NEIS visualization system; initial verification system in place for hydrostatic model comparisons; infrastructure to begin delivery of data and NEIS in real-time research mode for the Open Data Initiative.

Besides the specific milestones that have been met, one major achievement has been the building of collaboration between different organizations or teams within NOAA and with the partners at NCAR and NRL in order to focus on the common goal of improving the nation’s global forecast system. Every aspect of HIWPP has required cross-collaboration in order reach the plan milestones and to complete the major achievements listed above.

In preparation for year 2 of HIWPP, the entire project team did a thorough review of the project plan and milestones, and updated the plan to reflect adjustments in course that were appropriate. The revised plan was reviewed and approved by the HIWPP Executive Oversight Board. The most significant adjustments to the plan were made within the Non-hydrostatic Models sub-project in order to align with newly-formed NOAA R2O initiatives. In this way, HIWPP has not only begun the process of advancing the NOAA global forecasting capabilities, but is also supporting continued progress along the pipeline of research to operations beyond the end of this project.

During FY2014, a new NOAA R2O initiative was established with the objective of building the Next Generation Global Prediction System (NGGPS) that will be the foundation for the operating forecast guidance system for the next several decades. NGGPS will build upon HIWPP results and HIWPP project members, especially within the Non-hydrostatic Global Models sub-project, have worked closely with the NGGPS team to align HIWPP efforts with this new initiative, thus enhancing progression along the research-to-operations (R2O) pipeline.

As part of the NGGPS effort, a committee was formed in August 2014 named the Advanced Computing Evaluation Committee (AVEC) to provide Level-1 technical evaluation of High Performance Computing (HPC) suitability and readiness of NGGPS candidate models. Initial benchmark test definitions have built upon idealized test cases defined for HIWPP. HIWPP team members have collaborated with the AVEC team to further define benchmark testing, and the members of the MPFG/GPU optimization team have contributed significantly to the committee.

High Performance Computing (HPC) resources have been a particular challenge to this project. As we push the envelope toward higher model resolutions, HPC resources required to support the model research increase by levels of magnitude. Additional computational resources, which have been funded through other Sandy Supplemental projects, will be essential for model development as HIWPP moves into its second year.

The new supercomputer “theia”, which is planned to replace the current “zeus” research system, is expected to become available in March 2015. This resource will be essential to continue real-time runs of high-resolution hydrostatic models, to run the next phase of non-hydrostatic model tests, and to continue research efforts for the Moving Hurricane Nest.

A second massively parallel, fine grain (MPFG) system procured through Sandy Supplemental funding is expected to come online in the winter of 2016. HIWPP plans to utilize this system to conduct further optimization, testing and demonstration of the high-resolution non-hydrostatic dynamical cores. Once more is known about the capabilities of this new system, HIWPP will coordinate with NGGPS to refine current plans and optimize the impacts and benefits of this activity.

As we move into FY2015, HIWPP will begin producing the real-time research products that are part of the Open Data Initiative. Real-time data from the hydrostatic models will be made available to interested parties in the public, private, and academic sectors. The NEIS visualization system will also be available for use to visualize these and other data sets. In turn, the Open Data users will be encouraged to provide feedback to the model developers with the objective of providing additional viewpoints to help improve forecast models.

During FY2015:

1. The Hydrostatic Models sub-project will continue to evaluate and improve models, using tools and feedback provided through HIWPP. Data Assimilation using 4D ensemble-variational techniques and physics parameterization research will continue to be developed and evaluated within hydrostatic models, with the objective of having new packages ready for operational use by the end of this period.
2. The Non-hydrostatic Models sub-project, in coordination with NGGPS and AVEC, will define benchmark tests for evaluating computational efficiency and maturity, and will then undertake the next major level of testing, comparing the five participating dynamical cores with tests using real data, as opposed to idealized data. A final project report, summarizing all testing will be completed. The MPFG task will continue their work to optimize code performance on new MPFG architectures.
3. The Moving Hurricane Nest sub-project will continue tuning and testing of HWRF nesting, physics and vortex initialization in NMMB, and will transition multiple telescopic two-way nesting capabilities into the multi-scale NMMB/NEMS framework. They will then use large scale retrospective tests to confirm the effectiveness of the implemented nest motion algorithm in the NMMB framework.
4. The NMME sub-project will complete the archive of enhanced NMME data, complete the setup of the NMME-based hurricane seasonal outlook procedure, and will test real-time NMME-based hurricane seasonal outlook.
5. Within the Test Program, new techniques for statistical post-processing will be evaluated and the most promising will be implemented. Version 2 of the NEIS visualization system will be developed, adding new capabilities and features. The verification team will continue work on a new integrated, interactive verification system with new capabilities for evaluating precipitation and ensembles. The team will also provide ongoing support for the Open Data Initiative distribution of real-time data and visualization tools, along with collected feedback from users over a one-year period, beginning in February, 2015 (anticipated).

In summary, HIWPP has made significant progress during the first year toward its objective of accelerating high-resolution global model development. Even more so, a foundation has been laid for major deliverables planned for the second year of the project.

High-Impact Weather Prediction Project (HIWPP)

Appendix A – Project Milestones and Status

Task num	Task name	Date Due	Description	Due - Qtr	Due - Fiscal Year	Status 10/1/2014
3.0	Proj Mgmt	10/31/13	Complete detailed project plan	Q1	2014	Completed
3.0	Proj Mgmt	06/30/14	Establish project web page	Q3	2014	Completed
3.0	Proj Mgmt	09/30/16	Project Completion	Q4	2016	
3.0	Proj Mgmt	09/30/16	Final project report completed and submitted to EOB	Q4	2016	
3.1	Hydrostatic Models	03/31/14	Identify participants, computer resources, and determine model configurations for hydrostatic tests	Q2	2014	Completed
3.1	Hydrostatic Models	06/30/14	Begin retro testing and tuning of 4D-En-Var with high-res GFS	Q3	2014	Completed
3.1	Hydrostatic Models	06/30/14	Begin retro runs of all hydrostatic models	Q3	2014	Runs begun for GFS and FIM; NAVGEM runs are pending resolution of model issues
3.1	Hydrostatic Models	09/30/14	Implementation of improved higher res GFS	Q4	2014	Delayed to Dec 2014
3.1	Hydrostatic Models	09/30/14	Config of 4D-En-Var finalized and begin cycling forecasts	Q4	2014	Completed
3.1	Hydrostatic Models	08/31/14	Prelim retro runs may be available	Q4	2014	Completed

3.1	Hydrostatic Models	09/30/14	Retro deterministic runs complete for FIM, NAVGEM. Complemented by GFS real-time parallel tests and retro GFS runs at ESRL.	Q4	2014	GFS runs available; FIM and NAVGEM in progress, expected completion in Nov 2014
3.1	Hydrostatic Models	12/30/14	Implementation of higher res GEFS, GSI	Q1	2015	
3.1	Hydrostatic Models	10/31/14	Decision made on quasi-real-time ensembles. Quasi-real-time deterministic and ensemble forecasts available. Decision on mini ensemble of high-res models made.	Q1	2015	
3.1	Hydrostatic Models	12/30/14	Configuration finalized for quasi-real-time high-res runs	Q1	2015	FIM finalized; NAVGEM expected in Dec
3.1	Hydrostatic Models	12/31/14	Begin quasi-real-time, high resolution runs of deterministic and ensemble hydrostatic forecasts	Q1	2015	FIM realtime runs begun; GFS running as parallel; NAVGEM hoping to begin soon
3.1	Hydrostatic Models	03/31/15	Feedback from beta testers collected and synthesized.	Q2	2015	
3.1	Hydrostatic Models	06/30/15	Draft report for submission to peer-reviewed journal.	Q3	2015	
3.1	Hydrostatic Models	09/30/15	Final report submitted to peer-reviewed journal.	Q4	2015	
3.1.1	DA/Ens /Physics	03/31/14	Parameters for stochastic physics tuned for DA and medium-range EPS using T574L64 semi-Lagrangian GFS ensemble.	Q2	2014	Completed
3.1.1	DA/Ens /Physics	03/31/14	Testing of EnKL TC relocation scheme finished	Q2	2014	Completed

3.1.1	DA/Ens /Physics	06/30/14	Incremental analysis update (IAU) implemented and tested within 4D-En-Var using GFS model	Q3	2014	Completed
3.1.1	DA/Ens /Physics	06/30/14	Balance constraint for EnKL analysis implemented and tested using GFS model	Q3	2014	Completed
3.1.1	DA/Ens /Physics	09/30/14	Initial configuration of quasi-real-time 4D-EnVar analysis system complete	Q4	2014	Completed
3.1.1	DA/Ens /Physics	03/31/15	Results of 4D-EnVar testing used to recommend a preliminary test package to NCEP/EMC as a candidate for operational implementation	Q2	2015	
3.1.1	DA/Ens /Physics	09/30/15	Tests completed for perturbation of land and sea surface state within ensembles	Q4	2015	
3.1.1	DA/Ens /Physics	09/30/15	Tests completed for effect of increased ensemble size in 4D-En-Var from 80 to 320 members	Q4	2015	
3.1.1	DA/Ens /Physics	12/31/15	Add advanced ensemble-based quality control to 4DEnVar system	Q1	2016	
3.1.1	DA/Ens /Physics	12/30/15	Interface to 4D-En-Var GSI system completed for selected non-hydrostatic core	Q1	2016	
3.1.1	DA/Ens/Physics	12/30/15	Stochastic microphysics scheme ported to selected dycores	Q1	2016	

3.1.1	DA/Ens /Physics	09/30/16	Evaluation complete for impact of stochastic microphysics scheme in cycled non-hydro DA and forecast system	Q4	2016	
3.1.1	DA/Ens /Physics	09/30/16	Evaluation complete of selected non-hydro model within cycled 4D-En-Var system	Q4	2016	
3.1.2	Parameterizations (1)	12/30/13	Hire postdoc at NCEP	Q1	2014	Completed. Started 7/15/2014
3.1.2	Parameterizations (1)	12/31/13	Begin including new physics modules in single-column model based on GFS	Q1	2014	Diagnostic implementation begun
3.1.2	Parameterizations (1)	12/31/14	Implementation of new physics modules completed for GFS single-column model (SCM)	Q1	2015	Delayed 9 mos. due to delay in hiring
3.1.2	Parameterizations (1)	12/31/14	SCM experiments with current operational GFS physics and new physics completed and results compared.	Q1	2015	Delayed 9 mos. due to delay in hiring
3.1.2	Parameterizations (1)	03/31/15	DOE ARM program obs/analyses used to initialize SCM and evaluate SCM performance	Q2	2015	Delayed 9 mos. due to delay in hiring
3.1.2	Parameterizations (1)	03/31/15	Physics tuned if necessary	Q2	2015	Delayed 9 mos. due to delay in hiring
3.1.2	Parameterizations (1)	03/31/15	Advanced physics included in GFS	Q2	2015	Delayed 9 mos. due to delay in hiring
3.1.2	Parameterizations (1)	06/30/15	Version of GFS with advanced physics complete.	Q3	2015	Delayed 9 mos. due to delay in hiring

3.1.2	Parameterizations (1)	06/30/15	Testing begun to perform medium-range NWP forecasts with prescribed initial conditions from operational Global Data Assimilation System (GDAS)	Q3	2015	Delayed 9 mos. due to delay in hiring
3.1.2	Parameterizations(2)	07/01/14	CIRES scientist hired	Q2	2014	Proceeding on schedule in spite of hiring difficulties.
3.1.2	Parameterizations (2)	09/30/14	Tuning of stochastic convective parameterization using EMC evaluation metrics finished	Q4	2014	This milestone is not completed to satisfaction. A few new implementations are still under investigation (using the EMC tuning metrics). Expect to finish this quarter.
3.1.2	Parameterizations (2)	03/30/15	Implementation and evaluation of aerosol awareness using observed and simulated AOD completed	Q2	2015	
3.1.2	Parameterizations (2)	09/30/15	Evaluation of scale awareness for case studies and shorter periods in non-hydrostatic modeling system finished	Q4	2015	
3.1.2	Parameterizations (2)	09/30/15	Peer reviewed publication submitted	Q4	2015	
3.1.3	GFS	03/31/14	Support scientists hired and trained; starting to collect GEFS initial conditions including initial perturbations	Q2	2014	One scientist, Dr. Wei Li to begin Sep 2014. Advertising for a 2nd scientist.
3.1.3	GFS	06/30/14	Started retrospective forecasts	Q3	2014	Completed

3.1.3	GFS	09/30/14	Forecast data exchanged with partners; statistical post-processing begun.	Q4	2014	Completed
3.1.3	GFS	12/30/14	Retrospective runs complete, multi-model evaluation and verification begun.	Q1	2015	Delayed; GEFS implementation expected early April 2015
3.1.3	GFS	03/31/15	Statistical post-processing complete; exchange of data complete.	Q2	2015	
3.1.3	GFS	06/30/15	Evaluation and verification complete. Comparison of experimental NAEFS including the FIM ensemble with operational NAEFS begun.	Q3	2015	
3.1.3	GFS	09/30/15	Comparison complete of experimental NAEFS including FIM ensembles with operational NAEFS. Summary report and/or scientific manuscript written.	Q4	2015	
3.1.4	FIM	03/31/14	Identify participants, computer resources, and determine model configurations for hydrostatic tests	Q2	2014	
3.1.4	FIM	04/01/14	Begin retrospective runs of FIM hydrostatic model for deterministic and ensemble forecasts	Q3	2014	Delayed; expected Oct 2014
3.1.4	FIM	06/30/14	Initial FIM verification results produced for retro runs	Q3	2014	Delayed; expected Nov 2014
3.1.4	FIM	11/15/14	Retro runs for 1-yr period for deterministic forecasts complete	Q1	2015	Delayed; expected Nov 2014
3.1.4	FIM	12/30/14	Configuration finalized for quasi-real-time high-	Q1	2015	

			res runs			
3.1.4	FIM	10/31/14	Decision made on quasi-real-time ensembles. Quasi-real-time deterministic and ensemble forecasts available. Decision on mini ensemble of high-res models made.	Q1	2015	
3.1.4	FIM	01/01/15	Begin quasi-real-time, high resolution runs of deterministic and ensemble hydrostatic forecasts	Q2	2015	
3.1.4	FIM	03/31/15	Feedback from beta testers collected and synthesized.	Q2	2015	
3.1.4	FIM	06/30/15	Draft report for submission to peer-reviewed journal.	Q3	2015	
3.1.4	FIM	09/30/15	Final report submitted to peer-reviewed journal.	Q4	2015	
3.1.5	NAVGEM	12/30/13	NAVGEM software for high-resolution ported	Q1	2014	
3.1.5	NAVGEM	06/30/14	NAVGEM dynamic core and model physics improved toward the targeted resolutions	Q3	2014	
3.1.5	NAVGEM	03/30/14	Software adapted and tested to produce forecast model output in appropriate format	Q1	2015	
3.1.5	NAVGEM	06/30/14	Limited retro runs examined for quality control and output format	Q1	2015	
3.1.5	NAVGEM	09/30/14	High-res and ensemble NAVGEM run for year-long retrospective time period.	Q1	2015	
3.1.5	NAVGEM	01/01/15	Begin quasi-real-time ensemble and high-res forecasts	Q2	2015	

3.1.5	NAVGEM	09/30/15	Participated in evaluation of multi-model ensemble forecasts	Q4	2015	
3.2	Non-Hydrostatic Models	06/01/14	Baroclinic wave DCMIP test cast 4.1.0 delivered to Task Lead	Q3	2014	Completed
3.2	Non-Hydrostatic Models	07/01/14	Orographic gravity wave test case on a scaled small planet delivered to Task Lead.	Q4	2014	Completed
3.2	Non-Hydrostatic Models	08/01/14	Idealized supercell test case on a scaled small planet delivered to Task Lead	Q4	2014	Done (except for NIM which has not yet submitted complete results)
3.2	Non-Hydrostatic Models	09/01/14	Optional tropical cyclone test case (DCMIP 5.1) delivered to Task Lead	Q4	2014	Not done (no one elected to run the optional test)
3.2	Non-Hydrostatic Models	10/01/14	Report synthesizing the results of submitted tests completed	Q4	2014	Delayed to Nov 2014
3.2	Non-Hydrostatic Models	11/30/14	Modeling groups deliver preliminary benchmark packages	Q1	2015	
3.2	Non-Hydrostatic Models	02/15/15	Final benchmark codes ready	Q2	2015	
3.2	Non-Hydrostatic Models	03/01/15	2-3 day global forecasts run by all models at 3 km, initialized from NCEP GDAS analysis	Q2	2015	
3.2	Non-Hydrostatic Models	06/01/15	Report on all idealized, 3-km real-data tests, and benchmark results completed	Q3	2015	
3.2	Non-Hydrostatic Models	10/01/15	Level-2 testing of selected dycores completed in conjunction with NGGPS	Q4	2015	

3.2.3	MPFG/ GPU Optimizations	03/30/14	NIM benchmark code ready for MPFG procurement	Q2	2014	Completed
3.2.3	MPFG/ GPU Optimizations	12/31/15	NIM dynamics optimized for MPFG on TACC	Q1	2015	
3.2.3	MPFG/ GPU Optimizations	03/30/15	MPFG parallelization of GFS to FIM and NIM completed, integrated with dynamics, tested on TACC, ORNL	Q2	2015	
3.2.3	MPFG/ GPU Optimizations	04/01/15	Computational benchmark tests prepared and run jointly with NGGPS for all non-hydro dycores	Q3	2015	
3.2.3	MPFG/ GPU Optimizations	09/30/15	Updated MPFG parallelization for FIM,NIM completed	Q4	2015	
3.2.3	MPFG/ GPU Optimizations	12/30/15	Performance optimized for NIM and beginning to run on MPFG system	Q1	2016	
3.2.3	MPFG/ GPU Optimizations	12/30/15	Parallelization of selected non-hydrostatic model in progress on new MPFG system	Q1	2016	
3.3	Moving Hurricane Nests	02/28/14	Initial training on NMMB/NEMS completed; HPC resources procured; development branch within EMC subversion set up; HWRF components for transition to NMMB/NEMS identified/prioritized	Q2	2014	Completed
3.3	Moving Hurricane	06/30/14	NMMB configured as research model for	Q3	2014	Completed

	Nests		hurricanes; implementation of HWRF vortex initialization scheme in NMMB begun; implementation of HWRF nest motion algorithm in NMMB begun; transition to jet continuing.			
3.3	Moving Hurricane Nests	09/30/14	NMMB for hurricane forecasts mimics operational HWRF configuration; idealized capability for simulations developed; HWRF physics schemes and vortex initialization implemented	Q4	2014	HWRF physics and a version of vortex initialization implemented in NMMB. Idealized capability deferred to Q1FY15. Ocean coupling and post-processing deferred to Q2FY15 (HFIP dependencies)
3.3	Moving Hurricane Nests	12/30/14	Implementation of appropriate physics suite from HWRF completed; HWRF nest upgrades transitioned to NMMB; physics and dynamics turned	Q1	2015	HWRF physics transitioned to the NMMB/NEMS framework. Transition of nest upgrades and vortex initialization on track. Effectiveness and sanity checks on track. Conducted regional and global NMMB experiments for several tropical cyclones in the Atlantic and confirmed the workings of HWRF physics in NMMB. Impact of 2-way feedback is being documented in this quarter.

3.3	Moving Hurricane Nests	12/30/14	Vortex initialization completed; effectiveness of 2-way nesting, physics and vortex initialization for NMMB confirmed in case studies.	Q2	2015	HWRF physics transitioned to the NMMB/NEMS framework. Transition of nest upgrades and vortex initialization on track. Effectiveness and sanity checks on track. Conducted regional and global NMMB experiments for several tropical cyclones in the Atlantic and confirmed the workings of HWRF physics in NMMB. Impact of 2-way feedback is being documented in this quarter.
3.3	Moving Hurricane Nests	02/28/15	Preliminary tests completed on NMMB nest testing with HWRF physics and vortex initialization for tropical cyclone case studies	Q2	2015	On track
3.3	Moving Hurricane Nests	03/30/15	Multiple telescopic 2-way nesting in multi-scale NMMB/NEMS completed and tested.	Q3	2015	On track. Preliminary evaluation of multi-nest simulations in the basin-scale and global configurations is completed.
3.3	Moving Hurricane Nests	06/30/15	Report completed on NMMB nest testing with HWRF physics and vortex initialization for tropical cyclone case studies	Q3	2015	On track
3.3	Moving Hurricane Nests	06/30/15	Physics and vortex initialization fine-tuned for hurricane applications	Q3	2015	On track
3.3	Moving Hurricane Nests	09/30/15	Large scale retro tests performed; retuning completed if needed; effectiveness of nest motion algorithm in NMMB framework confirmed.	Q4	2015	On track. Heavily depends on available computational resources. Moderate risk.

3.3	Moving Hurricane Nests	12/30/15	Evaluation of storm structure and rainfall forecasts for land-falling storms complete	Q1	2016	On track
3.3	Moving Hurricane Nests	12/30/15	Retrospective testing of multi-nested NMMB/NEMS model complete and report completed	Q1	2016	Real-time demo can't be accomplished in Q1FY16 due to dependency on seasonal activity of hurricanes. Will change this milestone to "**Retrospective testing of multi-nested NMMB/NEMS model complete and report completed"**
3.4	NMME	07/31/14	Archive of enhanced NMME data for public access completed	Q4	2014	Partially complete. Anticipate that all data will be in archive by spring 2015 due to unanticipated slow transfer speed.
3.4	NMME	01/31/15	Evaluations of NMME-based hurricane seasonal outlook completed	Q2	2015	
3.4	NMME	03/31/15	NMME-based hurricane seasonal outlook procedure completed	Q2	2015	
3.4	NMME	04/30/15	Real-time test of NMME-based hurricane seasonal outlook completed	Q3	2015	
3.4	NMME	04/30/15	Final completion of archive of enhanced NMME data for public access	Q3	2015	
3.4	NMME	09/30/15	Evaluation of NMME-based severe weather environmental factors completed	Q4	2015	
3.5.1	Statistical Post Processing	03/31/14	Sample deterministic and ensemble data collected	Q2	2014	Completed

3.5.1	Statistical Post Processing	08/01/14	Preliminary technique and product available to Test Program for testing	Q4	2014	Completed
3.5.1	Statistical Post Processing	09/30/14	Real-time Statistical Post Processing product available	Q4	2014	Completed
3.5.1	Statistical Post Processing	02/01/15	Field alignment method evaluated	Q2	2015	
3.5.1	Statistical Post Processing	05/01/15	Methods to improve precip forecasts from Blender project evaluated	Q3	2015	
3.5.1	Statistical Post Processing	09/30/15	Most promising methods from FY15 evaluations implemented and integrated into existing framework	Q4	2015	
3.5.1	Statistical Post Processing	12/01/15	Methods using situational awareness, pattern recognition or inverse modeling evaluated.	Q1	2016	
3.5.1	Statistical Post Processing	12/01/15	Results of collaboration with groups doing ensemble work evaluated	Q1	2016	
3.5.1	Statistical Post Processing	12/30/15	Most promising methods from FY16 evaluations implemented and integrated into existing framework	Q1	2016	
3.5.2	NEIS	03/31/14	System architecture developed and hardware requirements identified	Q2	2014	Completed
3.5.2	NEIS	03/31/14	Disclaimer drafted for HIWPP experimental products, with EMC	Q2	2014	To be finalized after input from NWS
3.5.2	NEIS	03/31/14	Hardware procurement requisition complete	Q2	2014	Completed

3.5.2	NEIS	04/30/14	Beta NEIS version 1 system complete	Q3	2014	Completed
3.5.2	NEIS	07/31/14	Visualization linked to real-time data	Q4	2014	Completed
3.5.2	NEIS	10/01/14	Delivery and demo of NEIS version 1 system and development report completed	Q1	2015	Demo video of NEIS ver 1 at http://esrl.noaa.gov/neis/movies/ir_2010_megi_labeled.mp4
3.5.2	NEIS	12/30/14	Integration of verification output into NEIS completed	Q1	2015	
3.5.2	NEIS	03/30/15	Beta NEIS version 2 system complete, with volumetric and advanced analytics capabilities	Q2	2015	
3.5.2	NEIS	09/30/15	Delivery and demo of NEIS version 2 system and final development report completed	Q4	2015	
3.5.3	Verification	03/31/14	Preliminary testing of new VM for DB completed	Q2	2014	Completed
3.5.3	Verification	03/31/14	Test runs of EMC deterministic verification for HIWPP completed	Q2	2014	Completed
3.5.3	Verification	06/30/14	Human resources in place for code development	Q3	2014	Completed
3.5.3	Verification	08/01/14	Prototype system based on EMC (VSDB) system available for verification of hydrostatic model runs	Q4	2014	
3.5.3	Verification	08/01/14	Metrics, standards, and formats for advanced verification system completed with participation of project members	Q4	2014	Discussions with NCEP ongoing

3.5.3	Verification	09/30/14	Verification metrics for hydrostatic retro model runs and selected ensemble products produced and archived	Q4	2014	Waiting on retro runs from models
3.5.3	Verification	12/30/14	Verification metrics for hydrostatic real-time model runs and selected ensemble products produced and archived	Q1	2015	
3.5.3	Verification	12/30/14	Mid-range verification system based with MySQL database completed and available to project members	Q1	2015	In progress, expected Jan 2015
3.5.3	Verification	03/30/15	Advanced verification system with new capabilities completed	Q2	2015	
3.5.3	Verification	06/30/15	Advance verification system used for HIWPP verification	Q3	2015	
3.5.3	Verification	09/30/15	Final report completed	Q4	2015	
3.5.4	Real-time IT Ops	03/31/14	Community portal available for project	Q2	2014	Completed
3.5.4	Real-time IT Ops	03/31/14	Storage purchase requisition completed	Q2	2014	Completed
3.5.4	Real-time IT Ops	03/31/14	Data requirements for project year 1 defined and documented	Q2	2014	Completed
3.5.4	Real-time IT Ops	04/30/14	Plan in place to acquire all HIWPP required data in GSD's Central Facility	Q3	2014	Completed
3.5.4	Real-time IT Ops	05/31/14	Storage hardware procured and ready to install	Q3	2014	Hardware received 7/21/14, installed 9/9/14 but experiencing outages
3.5.4	Real-time IT Ops	06/15/14	Software components for data distribution completed	Q3	2014	Delayed until storage issues resolved

3.5.4	Real-time IT Ops	06/15/14	Enhanced IT infrastructure in place and tested, including hardware and software components	Q3	2014	Delayed pending resolution of storage hardware issues
3.5.4	Real-time IT Ops	06/30/14	Initial data from HIWPP members are flowing and available on Real-Time IT Ops infrastructure for internal testing	Q3	2014	Delayed by storage hardware and availability of real-time data
3.5.4	Real-time IT Ops	09/30/14	Real-time monitoring and support in place. Task report completed.	Q4	2014	Delayed pending resolution of storage hardware issues
3.5.4	Real-time IT Ops	12/31/14	Real-time distribution of hydrostatic model data reliably available through Open Data Initiative	Q1	2015	
3.5.4	Real-time IT Ops	12/31/14	Any necessary changes to community portal, real time monitoring, or IT infrastructure completed	Q1	2015	
3.5.4	Real-time IT Ops	04/30/15	Feedback from Open Data Initiative collected and made available to project members	Q3	2015	
3.5.4	Real-time IT Ops	09/30/15	Final report completed	Q4	2015	

High-Impact Weather Prediction Project (HIWPP)

Appendix B – HIWPP non-hydrostatic dynamical core tests: Results from idealized test cases

HIWPP non-hydrostatic dynamical core tests: Results from idealized test cases

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Background:

NCEP's current operational global atmospheric model dynamical core, the GSM, or Global Spectral Model, has been evolving in continuous use for over 30 years. The horizontal resolution of the GSM (~13-km in 2015) is approaching a grid spacing at which non-hydrostatic effects become significant. In addition, the current GSM may not be able to scale up to the size of peta-scale HPC systems. These facts will require adoption of a new atmospheric dynamical core for operational global prediction in the NWS within a decade. Since the global model touches almost every operational forecast NCEP produces, transitioning a new dynamical core (dycore) into operations is difficult and costly. Therefore, the NWS needs to ensure the new dynamical core is "future proof" and can serve NOAA's needs for at least 20 years. The HIWPP and NGGPS projects are collaborating to evaluate candidate non-hydrostatic dynamical cores with a battery of tests. The initial phase of testing under HIWPP has been completed. Each dynamical core ran a series of idealized tests, inspired by the Dynamical Core Intercomparison Project of 2012 (DCMIP; https://earthsystemcog.org/projects/dcmip-2012). The results of these tests are summarized in this document.

Participating Dynamical Cores:

The five candidate dycores are listed below, with sponsors in parentheses.

- **FV3** (GFDL) – Cubed sphere grid, finite-volume discretization (non-hydrostatic version of the hydrostatic core described in Lin, 2004).
- **MPAS** (NCAR) – Unstructured grid with C-grid variable staggering (Skamarock et al, 2012).
- **NEPTUNE** (NRL) – Flexible cubed sphere or icosahedral grid using a spectral element discretization with the Non-hydrostatic Unified Model of the Atmosphere (NUMA) core (Giraldo et al, 2014).
- **NIM** (ESRL) – Non-hydrostatic Icosahedral Model (unstaggered finite-volume A-grid implementation).
- **NMMB** (EMC) – Finite-difference, latitude/longitude grid, global extension of regional model (Janjic and Gall, 2012).

Idealized Tests:

1) *Baroclinic wave test with embedded fronts (DCMIP test case 4.1)*. This case was chosen because it elucidates the behavior of the models when the dynamics strongly forces the solution to the shortest scales resolved by the model (in this case, a strong frontal zone). It also is useful to illustrate the impact of increased truncation errors near quasi-singular points on the computational grid (such as the corners of the cubes on the cubed sphere grid, and the pentagonal cells on the otherwise hexagonal icosahedral grid).

   - Integration length: 20 days
   - Resolution: horizontal 120/60/30 and 15km. 30 and 60 vertical levels.
   - 1/0.5/0.25/0.125 degree grids for 120/60/30/15 km runs.
   - Model Top: ~44km/2.26hPa
   - No invariant tracers, output on 14 pressure levels (winds, temp and vorticity) plus surface pressure/temp and 10-m winds.

2) *Non-hydrostatic orographic mountain waves on a reduced-radius sphere (without rotation).* This case illustrates the ability of the models to simulate non-hydrostatic gravity waves excited by orography, an important phenomena not well simulated in today's hydrostatic forecast models. The small-planet approximation allows for resolutions to be achieved where non-hydrostatic effects are significant at much reduced computational cost. The effect of the spherical metric terms is exaggerated on the small-planet, but by designing the test so that the dynamics is focused in equatorial regions these effects are minimized.

   - **Case M1**: Uniform flow over a ridge mountain. This is a modified version of DCMIP case 2.1 with a quasi-2D mountain ridge as described in the NCAR document (http://cog-esgf.esrl.noaa.gov/site_media/projects/hiwpp/HI-WPP-mtn-new.pdf , equation 12) with a ridge height of 250m. The model top is positioned at 20km (instead of 30 km) with an absorbing layer above 10-km, a horizontal resolution of 1.1 degrees (~720 meters) and a vertical grid spacing of approximately 500 meters. Sphere radius reduction factor 166.7

   - **Case M2**: Uniform flow over a circular mountain. This case follows DCMIP case 2.1 (no vertical shear with a Schär-type circular mountain). Horizontal grid spacing 0.55 degrees (~360 meters). Vertical grid spacing approximately 250 meters. Other parameters as in Table XIII of DCMIP test document, except X=166.67 instead of 500.

- **Case M3**: Vertically sheared flow over a circular mountain. This case follows M2, except with vertical shear as defined by the parameter cs in Table XIII of DCMIP test document (https://earthsystemcog.org/site_media/docs/DCMIP-TestCaseDocument_v1.7.pdf) and the vertical resolution is 500 meters (instead of 250 meters).

3) *Idealized supercell thunderstorm on a reduced-radius sphere (without rotation).* Since the primary driver for developing global non-hydrostatic weather prediction models is the desire to explicitly simulate moist, deep convective processes, a test suite that did not verify the ability of candidate models to do this would be incomplete.

- Convection is initiated with a warm bubble in a convectively unstable sounding in vertical shear on a non-rotating reduced-radius sphere (with a reduction factor of 120).
- Detailed specification in the document (http://cog-esgf.esrl.noaa.gov/site_media/projects/hiwpp/Supercell-testcase.pdf) provided by NCAR.
- Two hour integrations at 4, 2, 1 and 0.5 km horizontal resolution.

Numerical diffusion parameters were not part of the test case specification, instead each modeling group chose diffusion parameters independently as they saw fit.

Baroclinic wave test results:

A baroclinic wave packet grows from a very small amplitude perturbation on an unstable zonal jet, reaching an amplitude at which nonlinear effects are strong and frontal collapse is well underway by day 9. The initial perturbation is applied in the Northern Hemisphere only, so the growth of instabilities in the Southern Hemisphere is due primarily to discretization errors at day 9. Figures B-1 and B-2 show the Southern Hemisphere 850 hPa vorticity, with the zonal mean removed to emphasize the grid imprinting signal, for each of the five models at the highest and lowest horizontal resolutions. The NMMB group submitted two sets of results, one with different values of numerical diffusion - both results are included. Only the 60 level results are shown, since the 30 level results are qualitatively similar.

The level of grid imprinting varies among the models, but is generally larger in the lower resolution case. The NEPTUNE model has very little grid imprinting, while NIM has a relatively larger signal on the coarsest (120-km) resolution but is comparable to MPAS and NMMB on the finest (15-km) resolution This is consistent with the order of accuracy used in the numerics, NIM being 2nd order and NEPTUNE using a higher-order spectral element method. Models with higher-order numerics have better numerical consistency across the 'special' points on the grid (the eight cube corners on the cubed sphere grid or the 12 pentagonal grid cells on the icosahedral grid). The noisy signal in the vorticity field in the NMMB solution is likely due to an interaction between the numerical dissipation and the polar filter needed to stabilize the solution on the lat/lon grid in polar regions, and appears to increase with the amplitude of the numerical diffusion. MPAS and FV3 solutions have smaller grid imprinting signals than NIM at the coarser resolutions, but larger than NEPTUNE. MPAS has slightly larger values at high resolution and FV3 having slightly larger values at lower resolution. The locations of the cube corners in the cubed sphere grid are evident in the FV3 solution, and wavenumber 5 and 10 patterns (excited by increased truncation error at the pentagonal grid cells) are evident in both NIM and MPAS solutions.

Figure B- 3 shows the 850hPa relative vorticity in the Northern Hemisphere day 9 for the high resolution case. All of the models create a large amplitude baroclinic wave packet, with strong fronts evident, but at this scale it is hard to see any differences between the solutions. Zooming in on the strongest frontal zone (Figures B-4 through B-7), reveals some interesting differences. The location of the cyclones is similar in the MPAS, NMMB and FV3 solutions, while the NIM solution is displaced slightly eastward, and NEPTUNE solution slightly westward, relative to the other solutions. It is not clear whether this is due to differences in the model numerics, differences in the placement of vertical levels, or small errors in the specification of the initial state[1]. An independent calculation was performed with a version of the hydrostatic spectral GFS dynamical core at 60-km resolution (not shown), and the phasing of the cyclones at day 9 agreed with the MPAS, NMMB and FV3 solutions. However, since this case has no analytic solution, it is not known definitively which model is most accurate with regard to the phasing of the cyclones. The MPAS and FV3 solutions are generally very similar. The NMMB solution exhibits banding structure in the vorticity field around the fronts associated with the strongest cyclone. The banding structure is evident at all horizontal resolutions, both for the high and low diffusion runs, but the scale of the bands decreases with increasing resolution.

Figure B- 8 shows the global kinetic-energy spectrum as a function of total wavenumber (ranging from wavenumber 40 to wavenumber 700), computed using spherical harmonic transforms of the lowest model level horizontal wind components. The spectrum is computed for day 9 of the 30-km solutions. Two reference lines are plotted on the figure, one showing the slope of a -3 power law spectrum (consistent with two-dimension turbulence theory) and one showing the slope of a -5/3 power law spectrum (consistent with fully three-dimensional turbulence). All of the models exhibit a spectrum shallower (steeper) than would be expected from two-dimension (three-dimensional) turbulence theory at larger scales, and a relatively steep spectrum at shorter scales (probably due to the effects of numerical dissipation). The relative sharpness of the drop-off in the spectra at the shortest wavelengths is proportional to strength and scale of the numerical dissipation in each model. The NMMB solutions exhibit a bump in the spectra between wavenumbers 200 and 400, which may be associated with the banding structure seen in the 850 hPa vorticity field near the strong fronts (Figure B-5).

Orographic mountain wave test results:

[1] The NIM developers did find and correct a bug in the initial condition specification for this case. The corrected results are shown. This reduced, but did not eliminate the eastward phase shift.

Figure B-9 shows vertical cross sections along the equator for test case M1, a quasi-two-dimensional ridge in barotropic, solid-body rotation flow on a reduced radius sphere (with a dry isothermal atmosphere). This is a modification of the circular mountain DCMIP test case (M2) that allows for more direct comparison with published solutions for a flow over infinite two-dimensional ridges in Cartesian geometry (see e.g. Schär et al, 2002 and Klemp et al, 2003). Also shown in Figure B-9 is the linear analytic solution for an infinite ridge on a flat plane. The gravity waves forced by this terrain have two dominant components: a larger-scale hydrostatic wave that is characterized by deep vertical propagation, and smaller-scale waves generated by the smaller scale terrain variations and characterized by rapid decay with height due to non-hydrostatic effects. All of the solutions agree qualitatively with the analytic solution, indicating that the model solutions are essentially linear at the equator, and the spherical metric terms are small, even on the reduced radius sphere.

Horizontal maps of vertical velocity at the model level closest to 8 km are shown in Figure B-10. There is no analytic solution for the behavior away from the equator in this case, since the analytic solution assumes no meridional variation on a flat plane. The meridional propagation of wave energy is broadly similar in the MPAS and FV3 solutions. The NMMB solution exhibits much less meridional propagation, likely due to its stronger numerical dissipation. NIM displays some grid-scale numerical noise in the extra-tropics because it does not use any artificial dissipation in this test case (besides whatever numerical diffusion is inherent to the spatial discretization). NEPTUNE exhibits stronger meridional propagation and stronger wave activity in the polar regions than the other models.

Figure B-11 shows vertical cross sections along the equator for test case M2, a circular mountain centered on the equator in an isothermal atmosphere with barotropic, solid-body rotation flow. This is identical to the DCMIP test case 2.1, except that that the sphere reduction factor was reduced from 500 to 166.7 to minimize the impact of the spherical metric terms and to prevent disturbances from circling the globe by the end of the two-hour integration. The analytic solution computed for flat-plane geometry is shown for reference. The gravity waves forced by this terrain have two primary components: a larger-scale hydrostatic wave that is characterized by nearly vertical propagation (similar to the M1 solution), and smaller-scale non-hydrostatic waves that propagate vertically and downstream. The same small-scale shallow non-hydrostatic trapped waves just above the terrain evident in the M1 solution are also present. Since the model top is placed higher in this test case, the solutions are show up to 20 km instead of 10 km. The primary differences seen in the model solutions are associated with the non-hydrostatic downstream propagating waves. MPAS, FV3 and NIM produce qualitatively similar solutions on the equator, which agree well with the flat-plane linear analytic solution. NMMB and NEPTUNE more strongly attenuate the waves in the downstream direction. However, NEPTUNE is the only model that uses the deep atmosphere equation set, which likely explains differences with the other models (all of which use a shallow atmosphere approximation)[2]. A solution computed with a halved

[2] In a deep-atmosphere model, the radial distance from the center of the earth (r) is not assumed to be constant; this appears in terms inversely proportional to r in the momentum equations (White et. al. 2005). On a reduced-radius sphere, this can have a significant effect since the depth of the atmosphere is the same order as the radius of the planet.

sphere reduction factor (83.33 instead of 166.7) is in better agreement with the other models, with less downstream wave attenuation (Figure B-12).

Case M3 is identical to case M2, except that the zonal flow includes vertical shear. This presence of stronger winds aloft traps the shorter wavelength components of the mountain waves in the lower atmosphere below the level where they become evanescent. The trapped waves become ducted and propagate horizontally downstream. There is no linear analytic flat-plane solution for this case. As for M1 and M2, the MPAS, FV3 and NIM solutions are all very similar along the equator (Figure B-14). NMMB strongly damps the ducted waves. The NEPTUNE solution is different than the other models, primarily in the phase propagation of the waves. This may be related to the fact that NEPTUNE does not use the shallow atmosphere approximation. There is much less meridional propagation of wave activity in this case relative to M1 (Figure B-15). The NMMB solution is much smoother than the other models, with much less horizontal structure evident in the vertical velocity field.

Idealized supercell test results:

This is an important test case, because it demonstrates the ability of the dynamical cores to simulate deep moist convection realistically. The ability to simulate deep moist convection explicitly is the primary motivation for developing global non-hydrostatic models. Here a very simple microphysics scheme is used (the warm rain microphysics scheme described in Kessler (1969)). The microphysical processes included are: the production, fall and evaporation of rain, the accretion and auto conversion of cloud water, the production of cloud water from condensation, and the effect of water loading on buoyancy. Each of the modeling groups implemented the same simple FORTRAN subroutine, provided by NCAR, to compute the warm-rain microphysics. Following the approach developed by Weisman and Klemp (1982) to simulate the basic characteristics of observed supercell thunderstorms, a warm bubble is initialized on the equator of a reduced radius sphere in a horizontally homogenous convective unstable environment characterized by large CAPE (~2200 m^2s^{-2}) and linear vertical wind shear below 5km. No boundary layer processes are included, and the models employ a free-slip lower boundary condition plus horizontal and vertical diffusion. As in all the other tests, each modeling group chose diffusion parameters independently.

The expected evolution (based upon Weisman and Klemp (1982) and many other similar idealized numerical studies) is the rapid development of a convective updraft, followed by splitting along the north and south flanks of the original storm's outflow boundary, producing two identical storms that propagate to the right and left of the mean shear vector.

Figure B-15 shows time series of the maximum vertical velocity for each of the models. Separate lines are shown for each of the four horizontal resolutions (500-m, 1-km, 2-km and 4-km). All of the models produce strong convective updrafts within 30 minutes, exceeding 30-50 meters per second at the highest resolution. The time step used in the 4-km and 2-km NIM runs was set to 2 seconds, which is identical to the 500-m run; otherwise significant updrafts did not form. NEPTUNE used an even shorter time step of 1 second for the 4-km run (as well as the 500-m, 1-km and 2-km runs). MPAS used a 4-km time step of 24 seconds, FV3 20 seconds and NMMB 8 seconds. NMMB produces much stronger updrafts at the 500-m resolution than the other models, exceeding 75 meters per second.

Figures B-16 through B-19 show horizontal maps of vertical velocity at the model level closest to 2500 meters, at 90 minutes into the integration. At this time, splitting of the original updraft has completed and all the models show identical convective updrafts north and south of the equator at the higher resolutions. In general, NMMB produces the noisiest solutions, FV3 the smoothest. This is partly a reflection of the diffusion choices made by the individual modeling groups. The FV3 group chose higher diffusion parameters to produce a nearly-converged solution at the highest resolution. For this reason, the FV3 solution lacks some of the finer scale features found in other solutions, such as the appearance of a rear-flank downdraft. The MPAS, NIM NEPTUNE and NMMB groups all chose similar diffusion parameters, yet the small scale details in their solutions are still significantly different. At the coarsest resolution (4-km), the convective updrafts are marginally resolved. MPAS and FV3 still produce solutions that retain the basic structure of the split cells present at the higher resolutions. The 4-km NEPTUNE solution captures the splitting cell although this solution is qualitatively different from the higher-resolution solutions. The NMMB model appears unable to simulate the basic aspects of the splitting supercell evolution at 4-km resolution. The 4-km NIM supercell is not completely split by 90 minutes.

Summary:

MPAS and FV3 produced remarkably similar solutions for all of the test cases, with minimal grid imprinting. NEPTUNE exhibits no discernible grid imprinting. Relative to the other models, NMMB exhibits stronger variability near the grid scale in the baroclinic wave and supercell test cases, and stronger damping in the mountain wave test cases. NIM exhibited the largest grid imprinting signal at coarser resolutions, and splitting of the supercell at 4-km resolution was delayed relative to FV3 and MPAS. NEPTUNE's mountain wave solutions differed from the other models likely due to the fact that it does not make the shallow atmosphere approximation. Both NEPTUNE and NIM exhibited small phase differences relative to the other models in the baroclinic wave test case.

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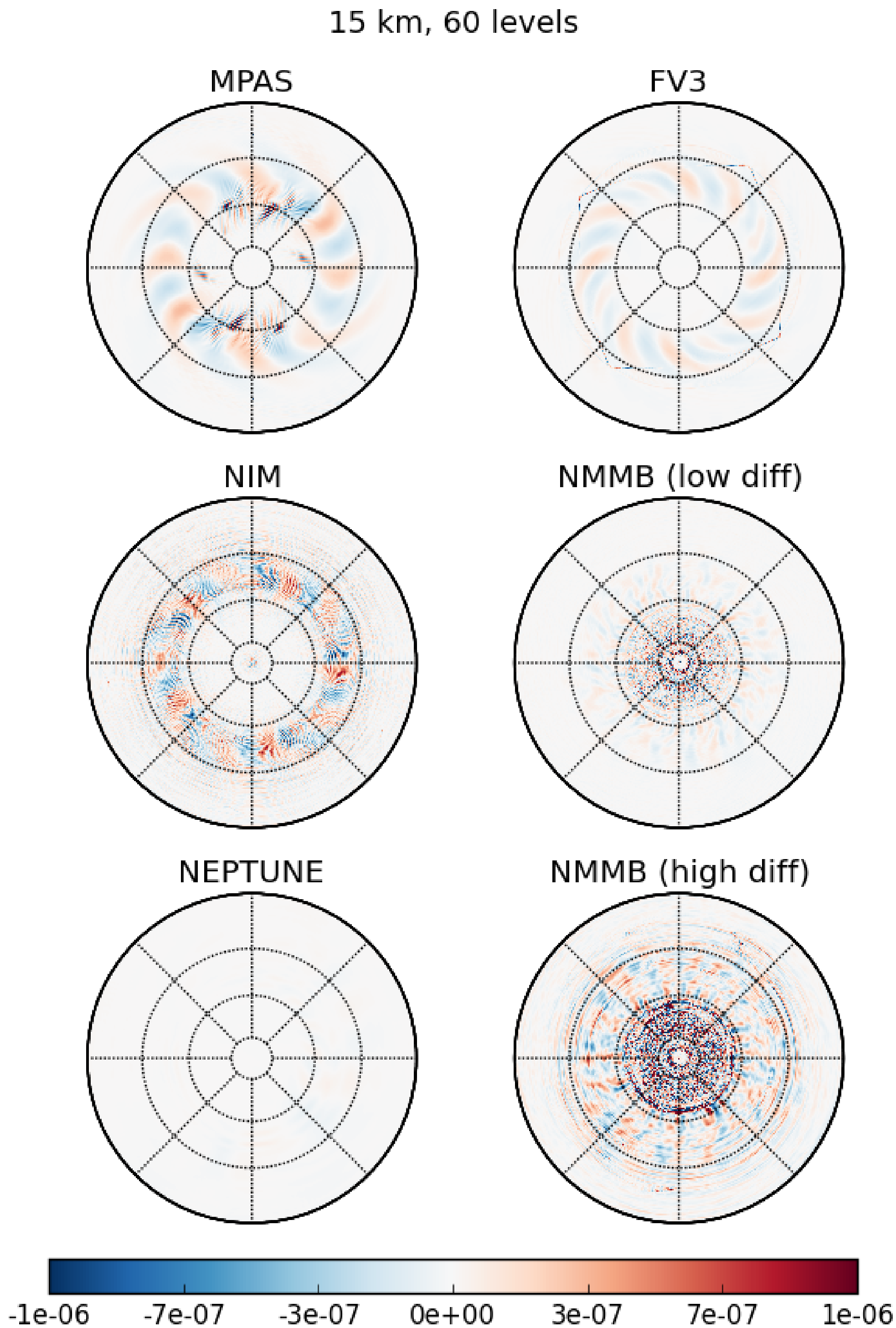

Figure B-1 Plots of Southern Hemisphere relative vorticity at 850hPa (with the zonal mean removed) for the high-resolution (nominally 15-km, with 60 levels) baroclinic wave test case at day 9. The outer edge of the plot is 20 degrees south latitude.

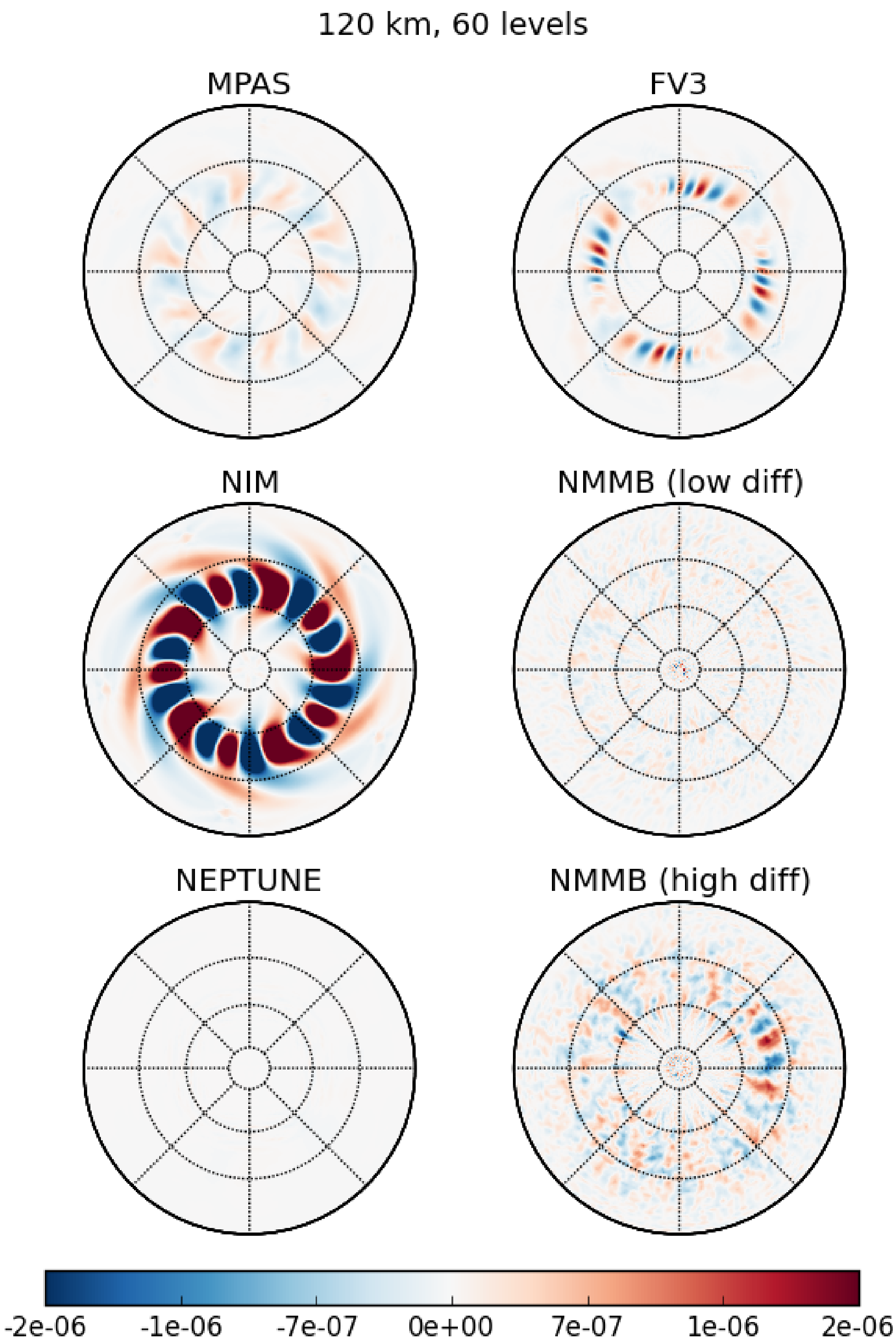

Figure B-2 As in Figure B-1, for the low resolution case (nominally 120-km, with 60 levels). The color scale is expanded by a factor of two relative to Figure B-1.

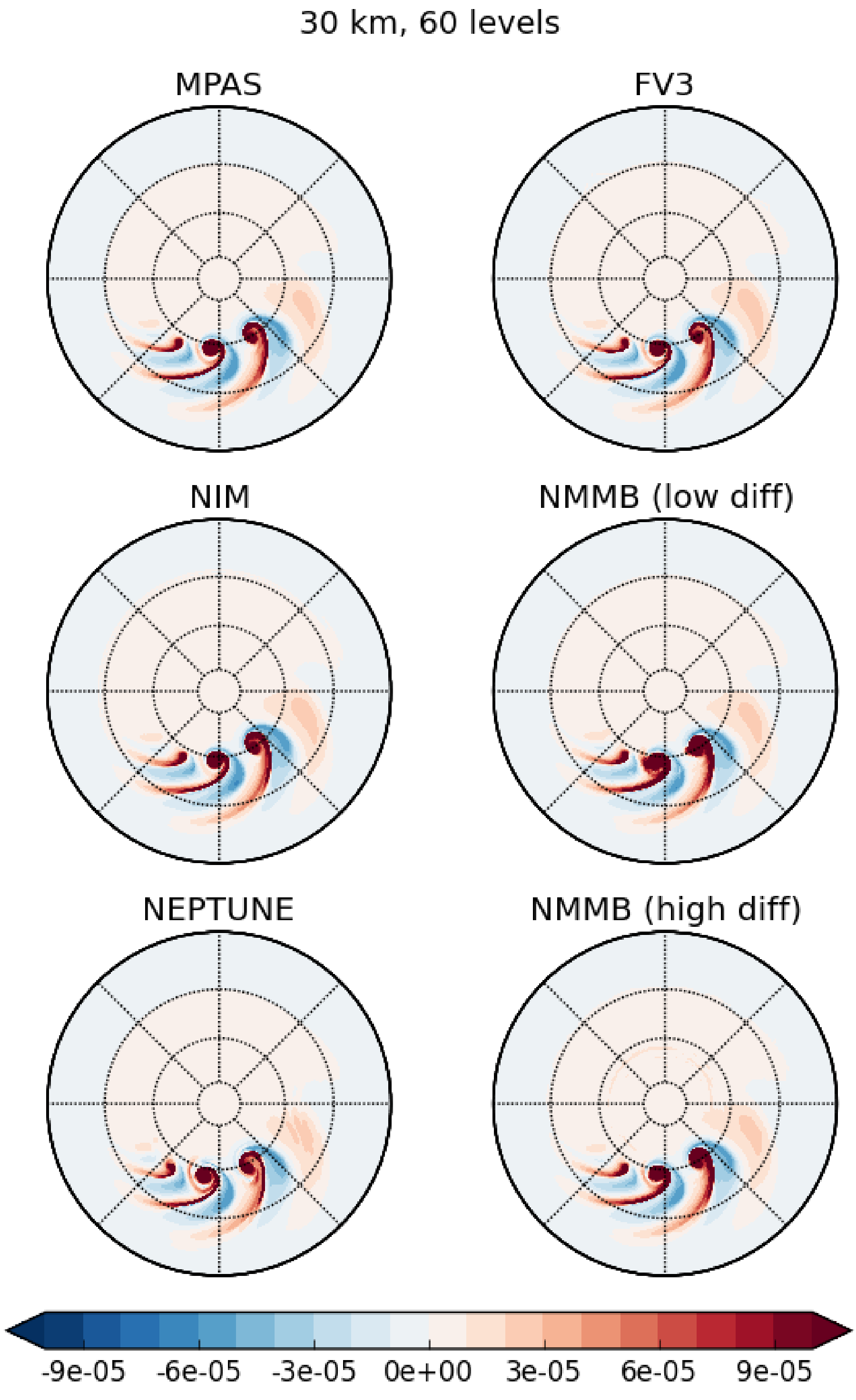

Figure B-3 Plots of Northern Hemisphere relative vorticity at 850hPa for the high-resolution (nominally 15-km, with 60 levels) baroclinic wave test case at day 9. Contour interval is 1 x 10^{-4} s^{-1}. The outer edge of the plot is 20 degrees north latitude

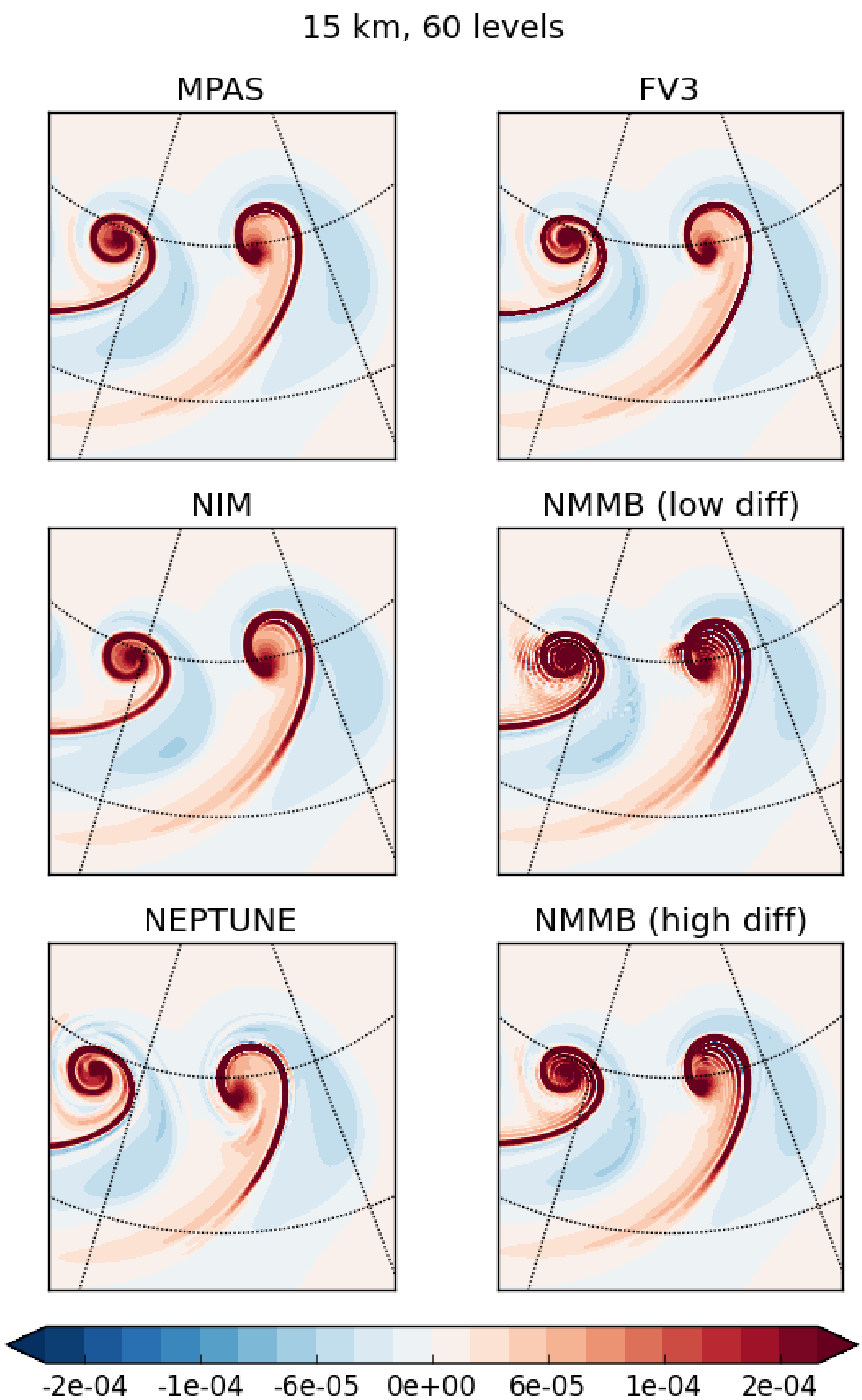

Figure B-4 Plots of relative vorticity at 850hPa zoomed in on the leading edge of the wave packet for the high-resolution (nominally 15-km, with 60 vertical levels) baroclinic wave test case at day 9. Contour interval is 1 x 10^{-4} s^{-1}.

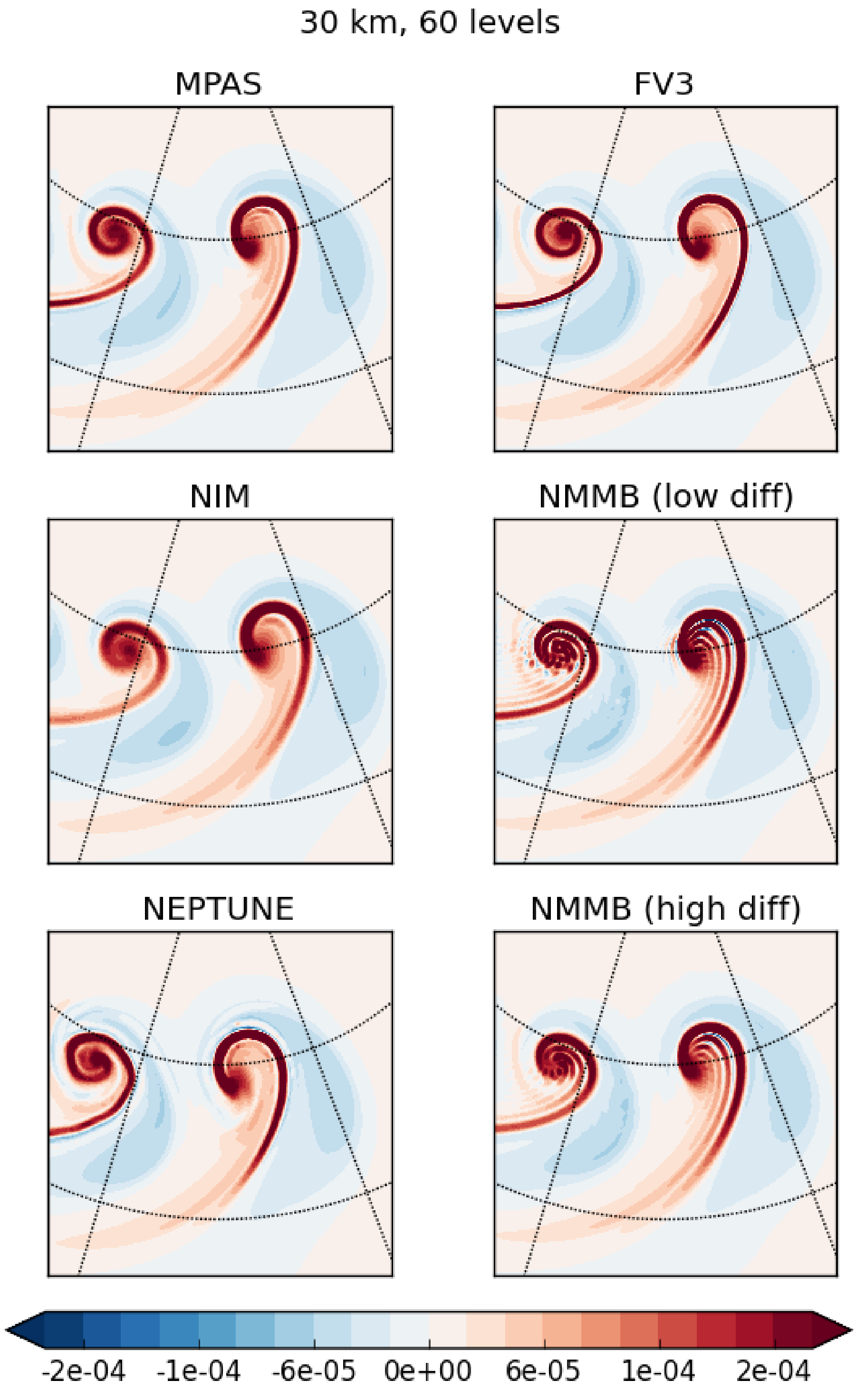

Figure B-5 As in Figure B-4, but for the (nominally) 30-km horizontal resolution runs

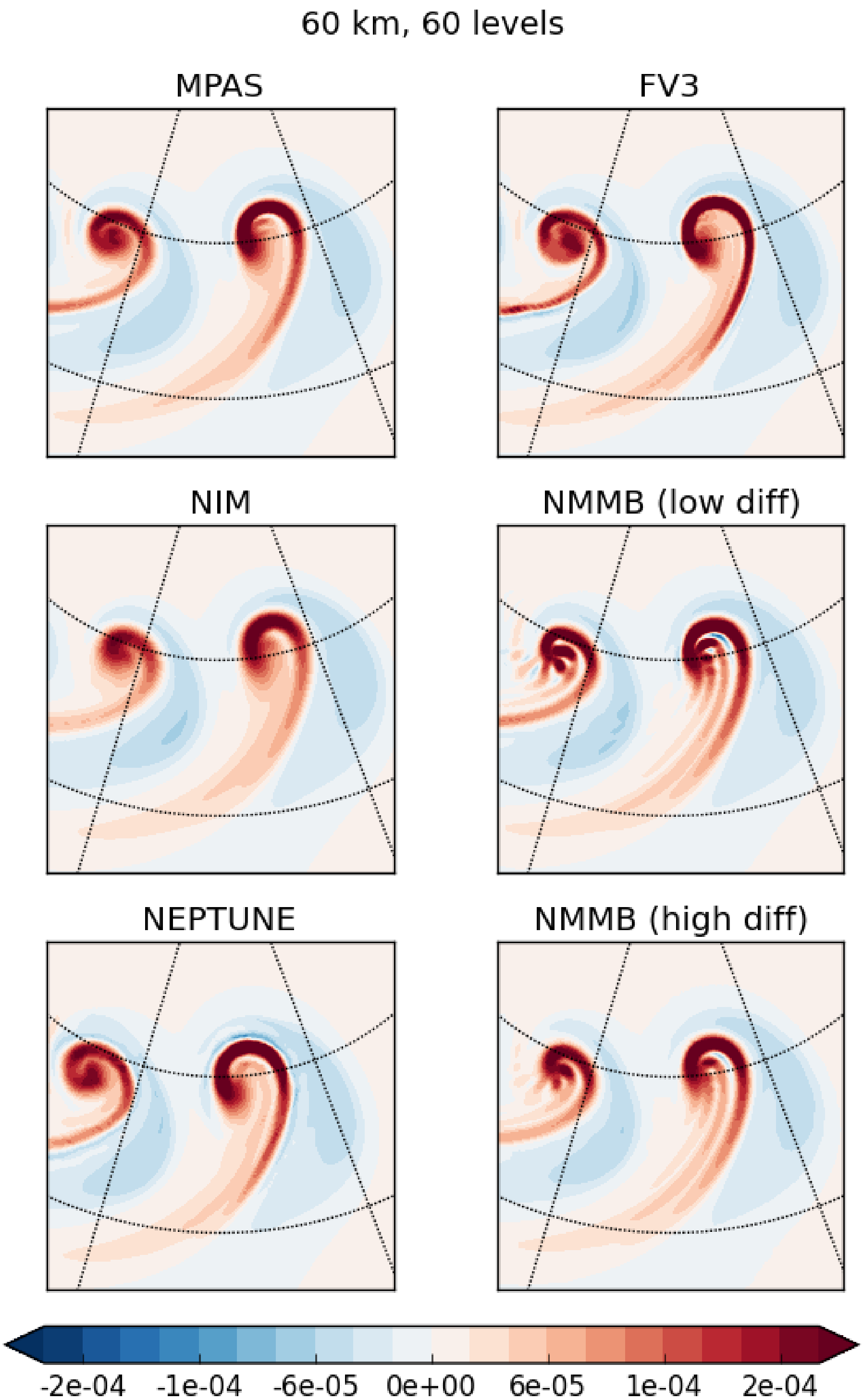

Figure B-6 As in Figure B-4, but for the (nominally) 60-km horizontal resolution runs

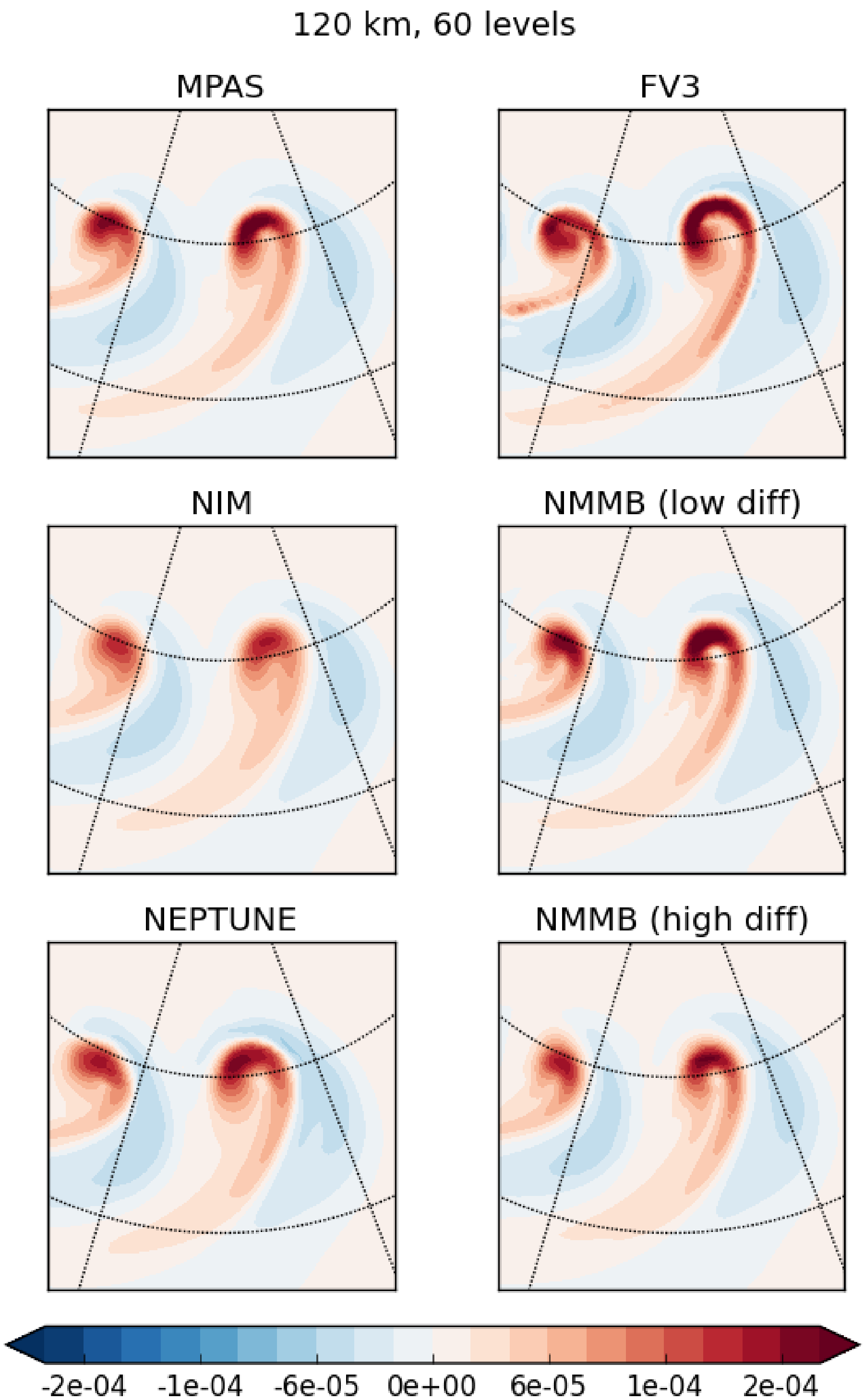

Figure B-7 As in Figure B-4, but for the (nominally) 120-km horizontal resolution runs.

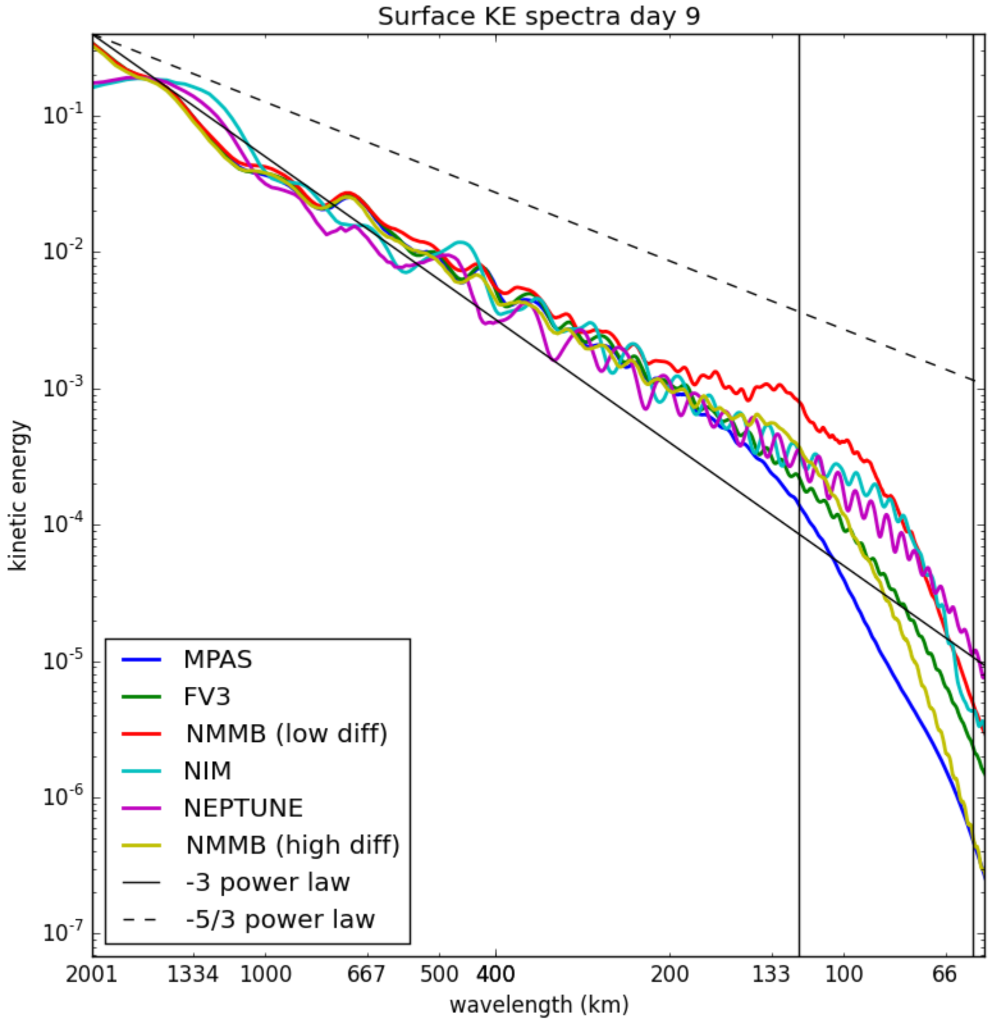

Figure B-8 Near surface global kinetic energy spectra (m^2/s^2) for day 9 of the 30-km baroclinic wave test case solutions. The x-axis is wavelength in km, with values ranging from total wavenumber 20 (~ 2000 km) to wavenumber 700 (~ 57 km), with a log-scale in total wavenumber. Two reference lines are plotted, one with a slope corresponding to a -3 power-law spectrum (solid black), and one with a slope corresponding to a -5/3 power-law spectrum. The two vertical lines represent wavelengths corresponding to two and four times the nominal grid resolution.

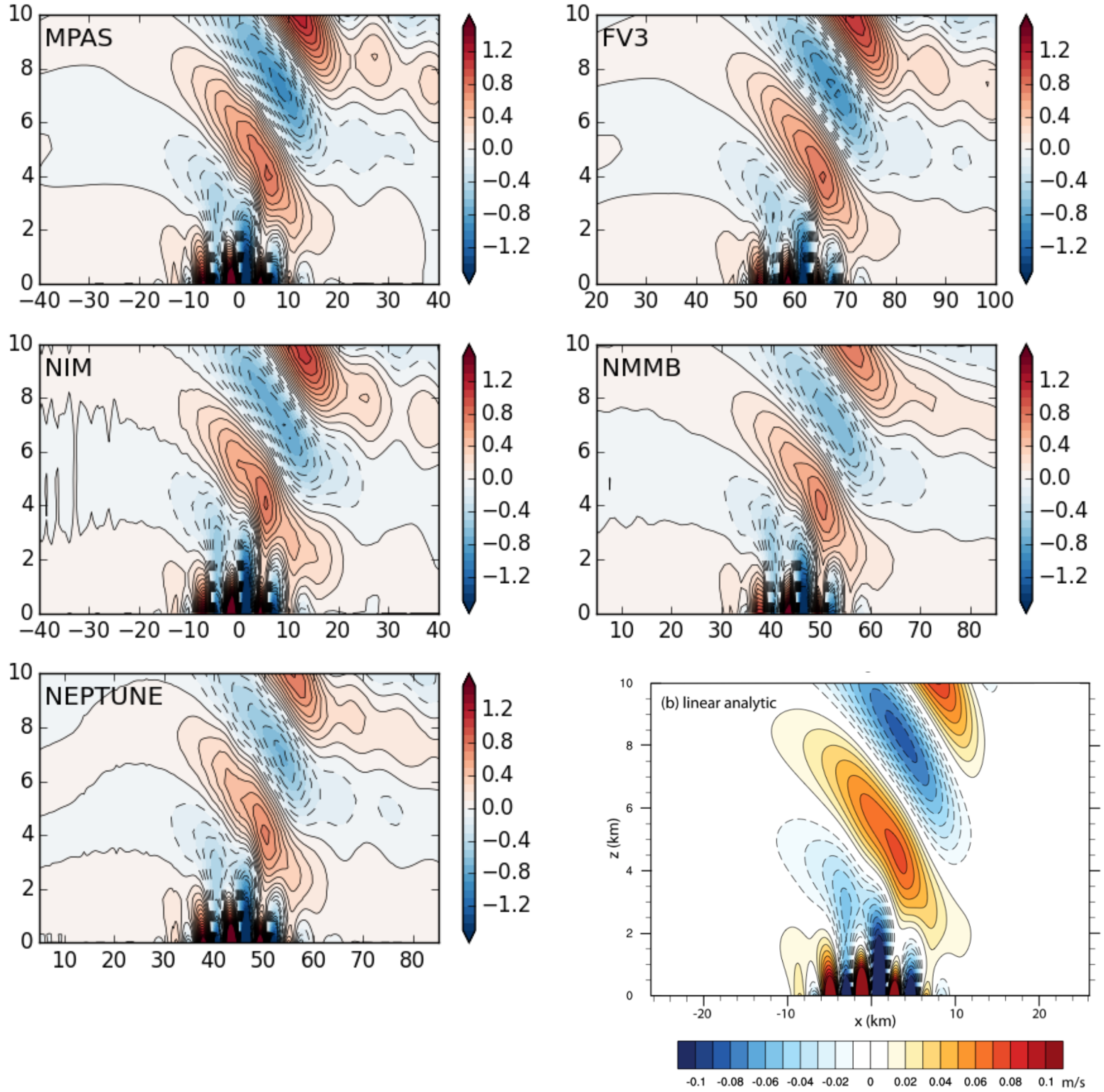

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Figure B-9 Cross sections of vertical velocity (m/s) along the equator for orographic mountain wave test case M1 on the reduced-radius sphere (quasi-2D ridge in a barotropic zonal flow). The x-axis is longitude (degrees) and the y-axis is altitude (km). The plot in the lower right corner is the analytical solution for the flat plane with a infinite ridge, excerpted from the test case description provided by NCAR, and available on the HIWPP web site (http://cog-esgf.esrl.noaa.gov/site_media/projects/hiwpp/HI-WPP-mtn-new.pdf).

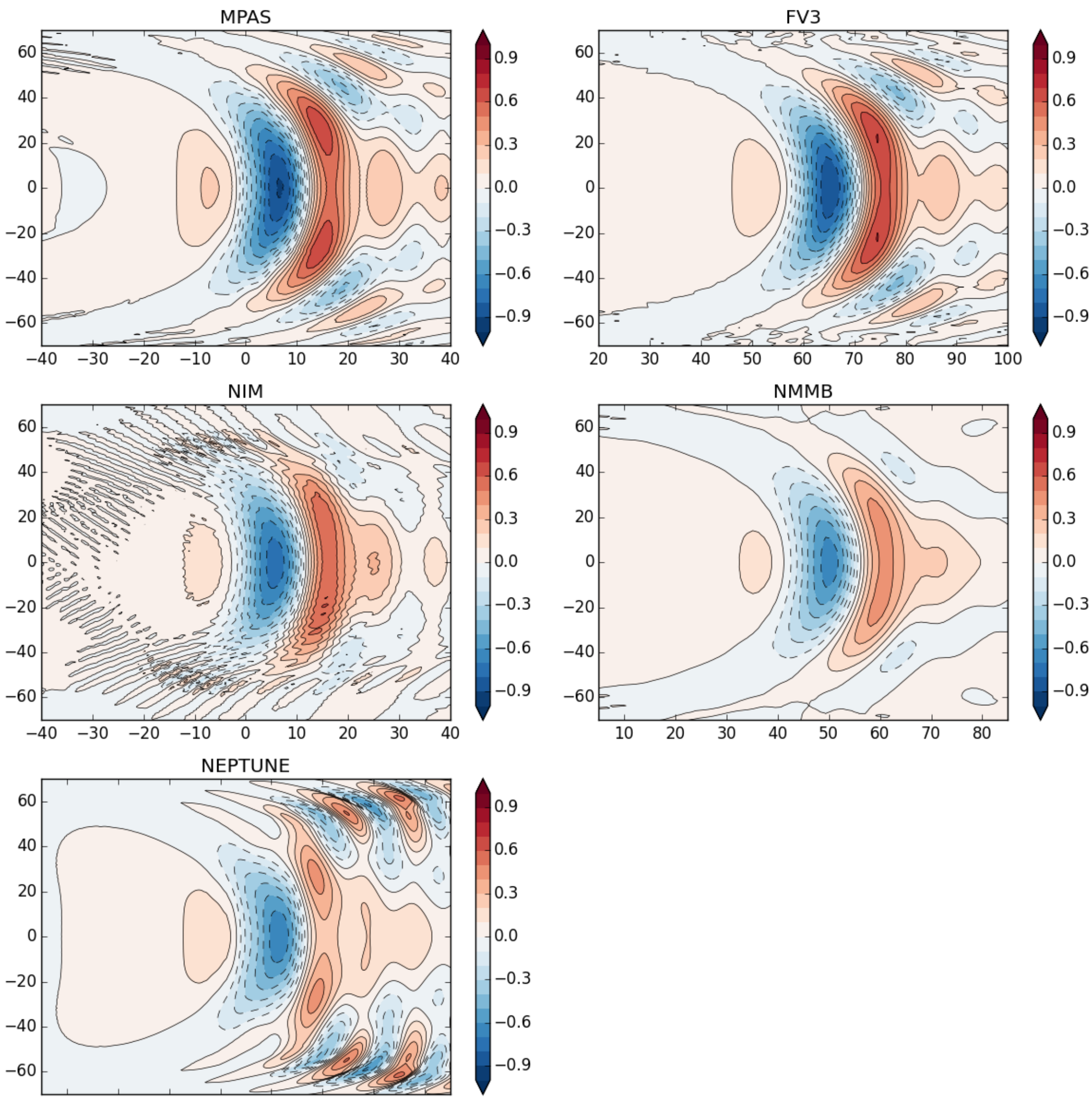

Figure B-10 Horizontal maps of vertical velocity (m/s) at the model level closest to 8 km elevation for the orographic mountain wave test case M1 on the reduced-radius sphere. The x-axis is longitude and the y-axis is latitude.

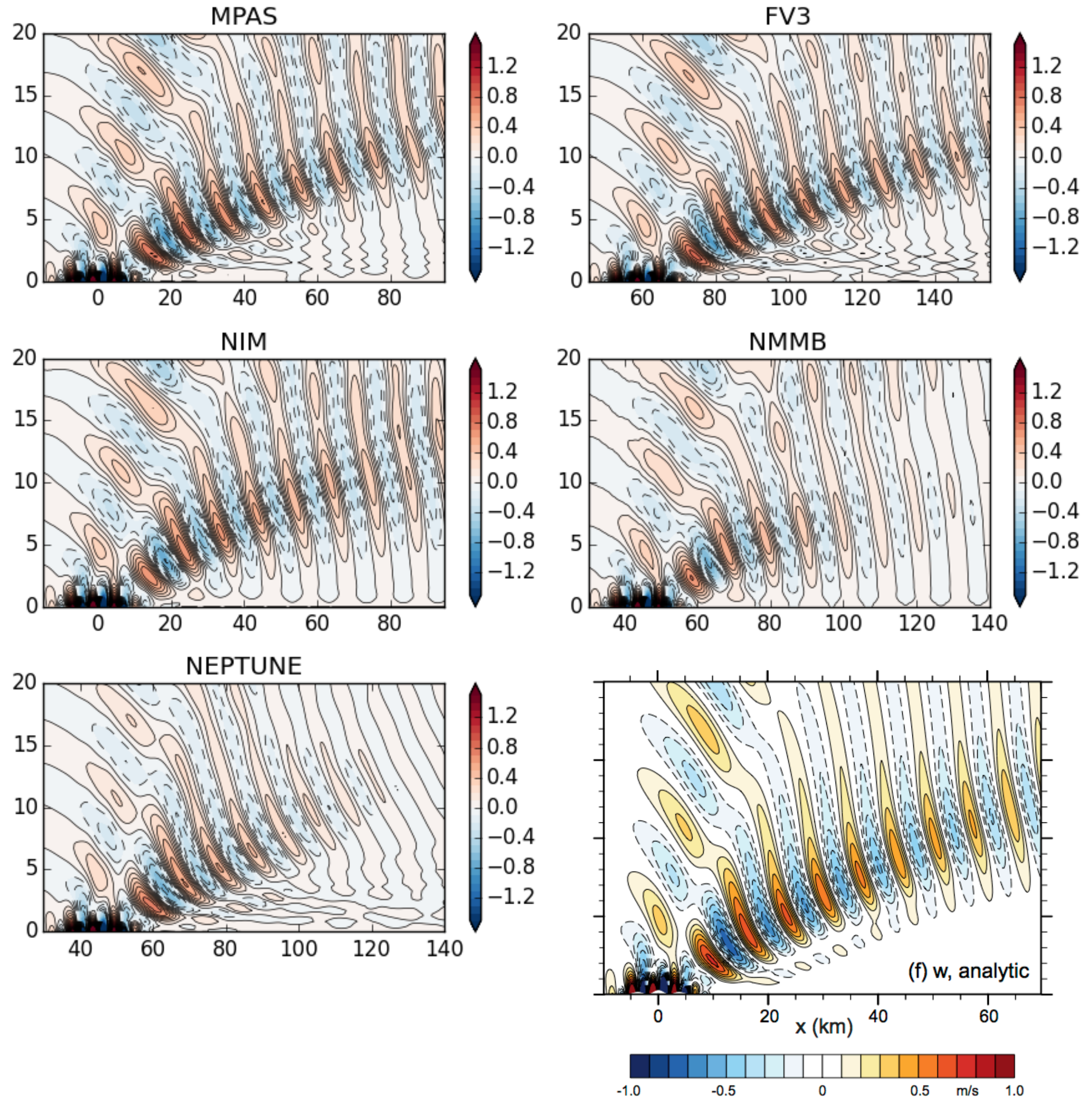

Figure B-11 Cross sections of vertical velocity (m/s) along the equator for orographic mountain wave test case M2 on the reduced-radius sphere (circular mountain in a barotropic zonal flow). The x-axis is longitude (degrees) and the y-axis is altitude (km). The plot in the lower right corner is the analytical solution for the flat plane, excerpted from the test case description provided by NCAR, and available on the HIWPP web site (http://cog-esgf.esrl.noaa.gov/site_media/projects/hiwpp/HI-WPP-mtn-new.pdf)

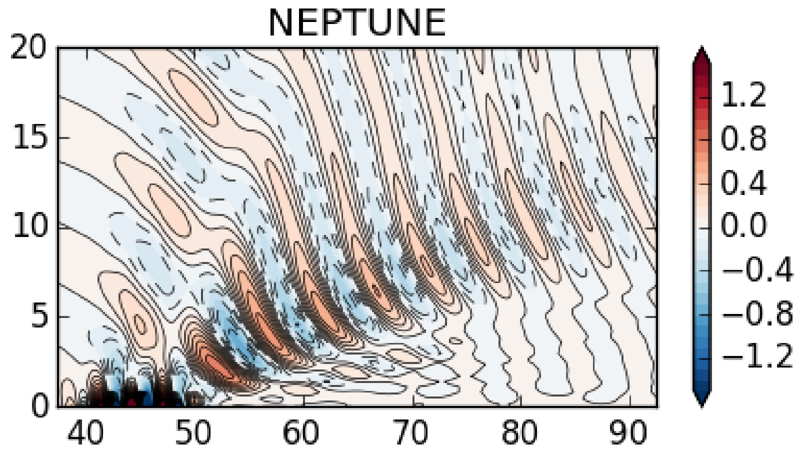

Figure B-12 As in Figure B-11 for the NEPTUNE solution, except computed on a sphere with doubled radius.

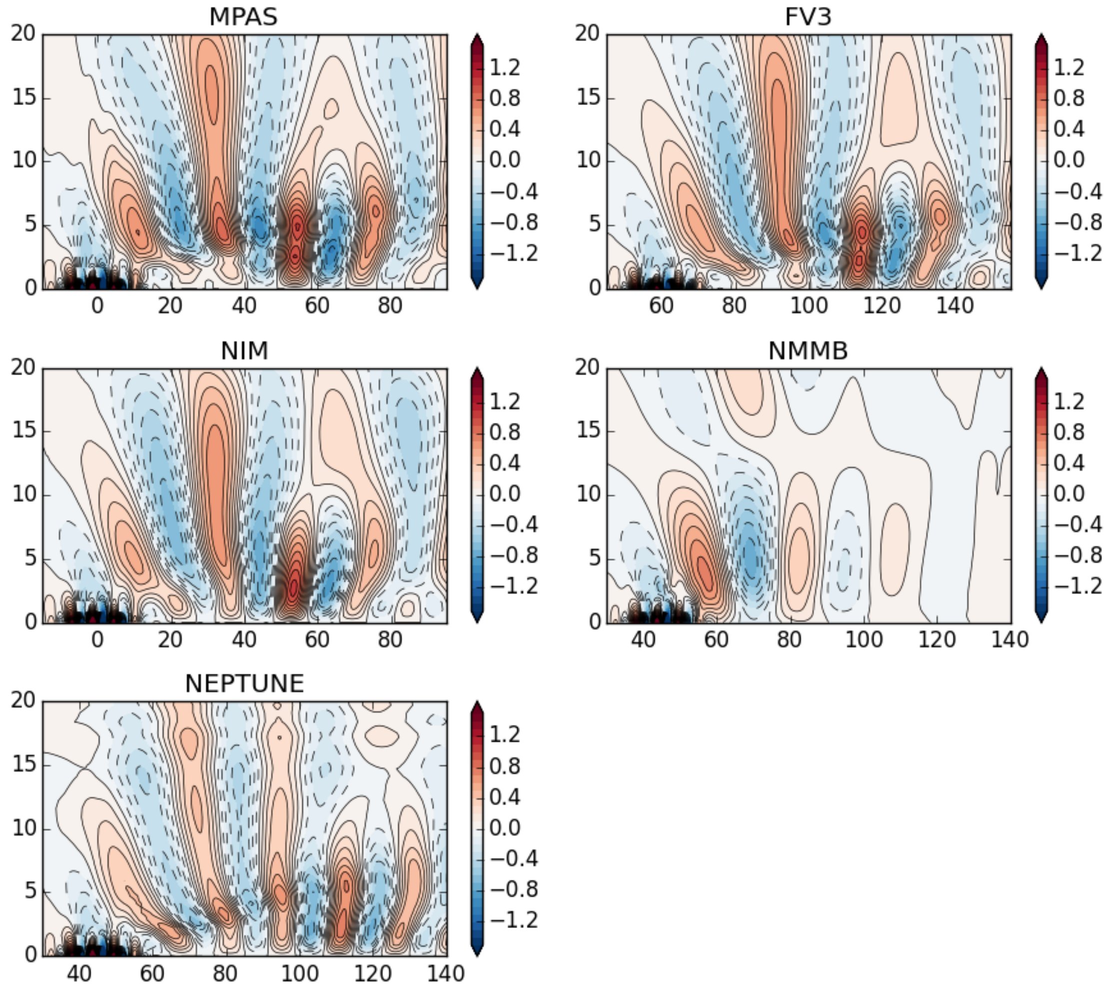

Figure B-13 Cross sections of vertical velocity (m/s) along the equator for orographic mountain wave test case M3 on the reduced-radius sphere (circular mountain with shear). There is no analytic solution for this test case. The x-axis is longitude (degrees) and the y-axis is altitude (km).

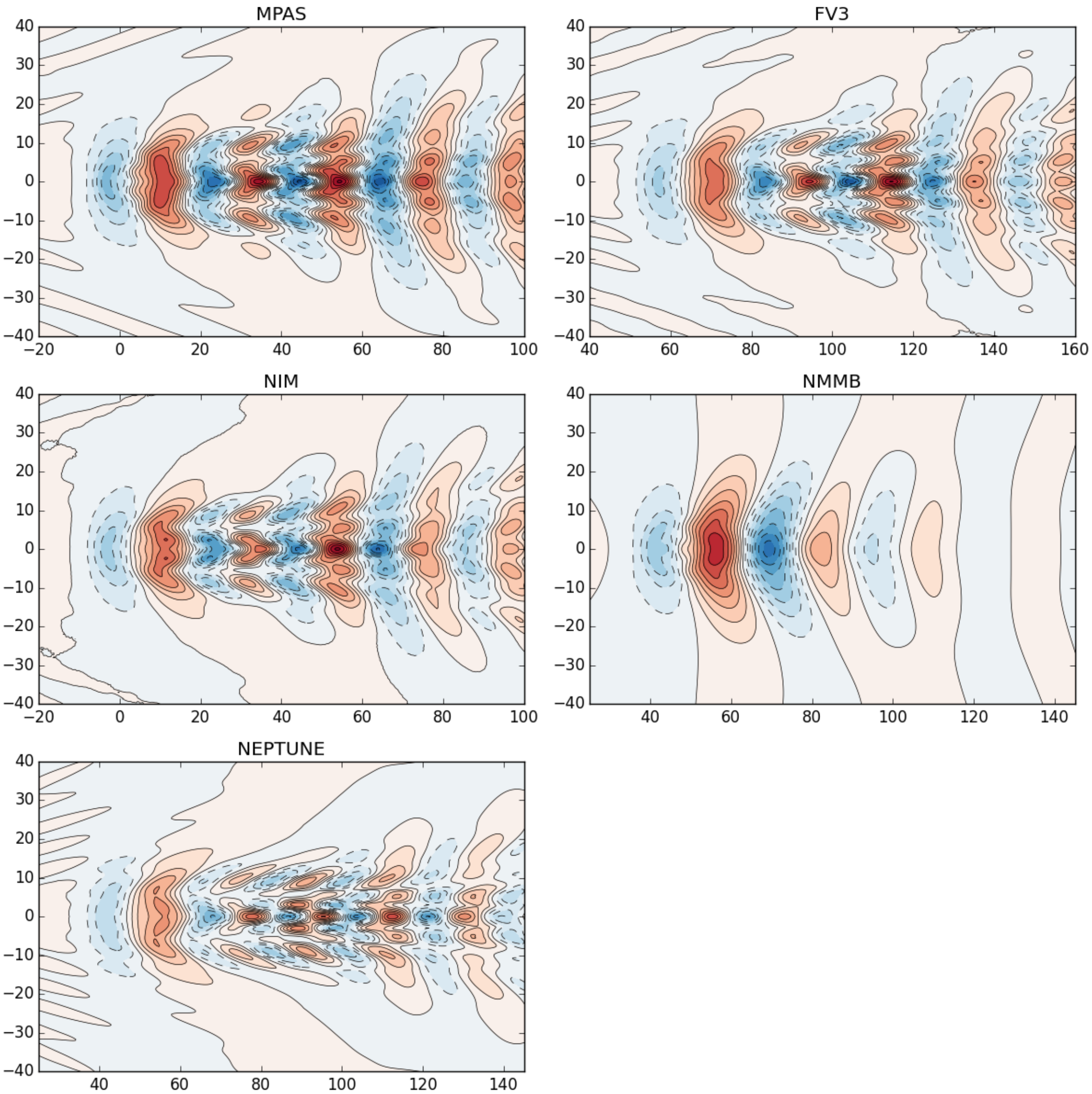

Figure B-14 Horizontal maps of vertical velocity (m/s) at the model level closest to 4 km elevation for the orographic mountain wave test case M3 on the reduced-radius sphere. The x-axis is longitude and the y-axis is latitude.

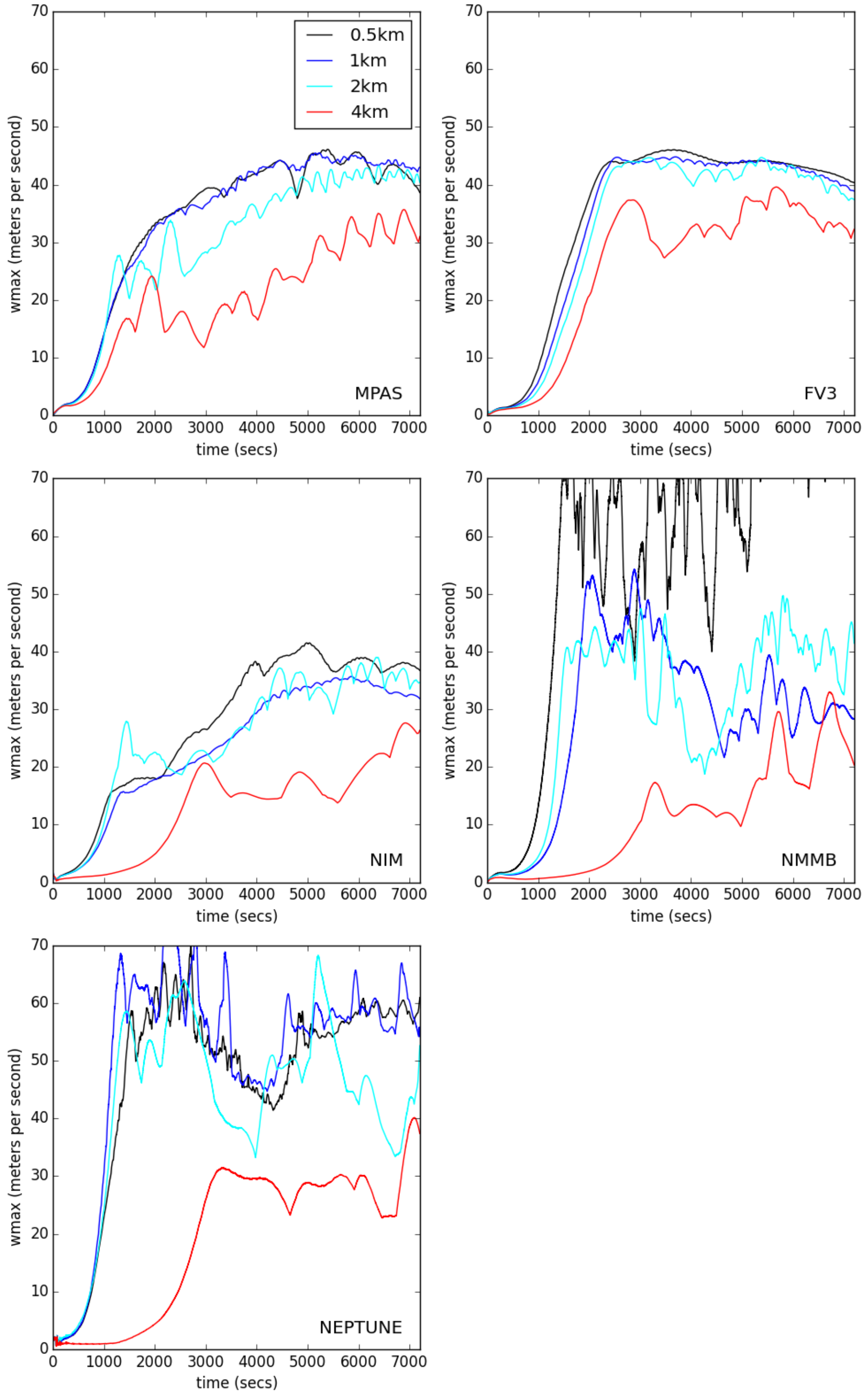

Figure B-15 Time series of the maximum vertical velocity for the supercell test case on the reduced radius sphere. Separate lines for each model represent the four different horizontal resolutions run (500-m, 1-km, 2-km and 4-km).

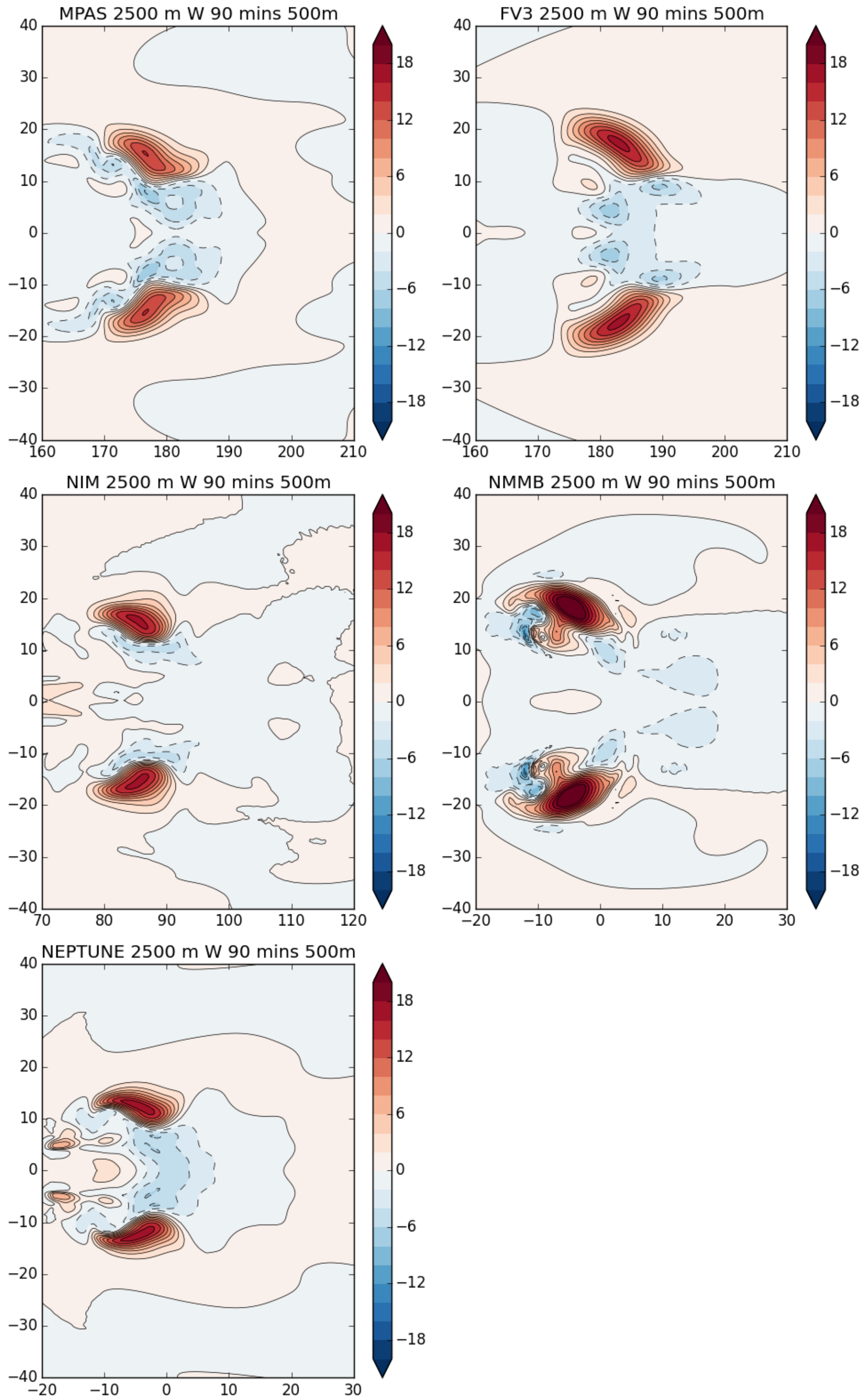

Figure B-16 Horizontal maps of vertical velocity (m/s) on the model level nearest 2.5 km for the supercell test case on the reduced radius sphere, for the 500-m resolution solution. The y-axis is latitude, and the x-axis is longitude.

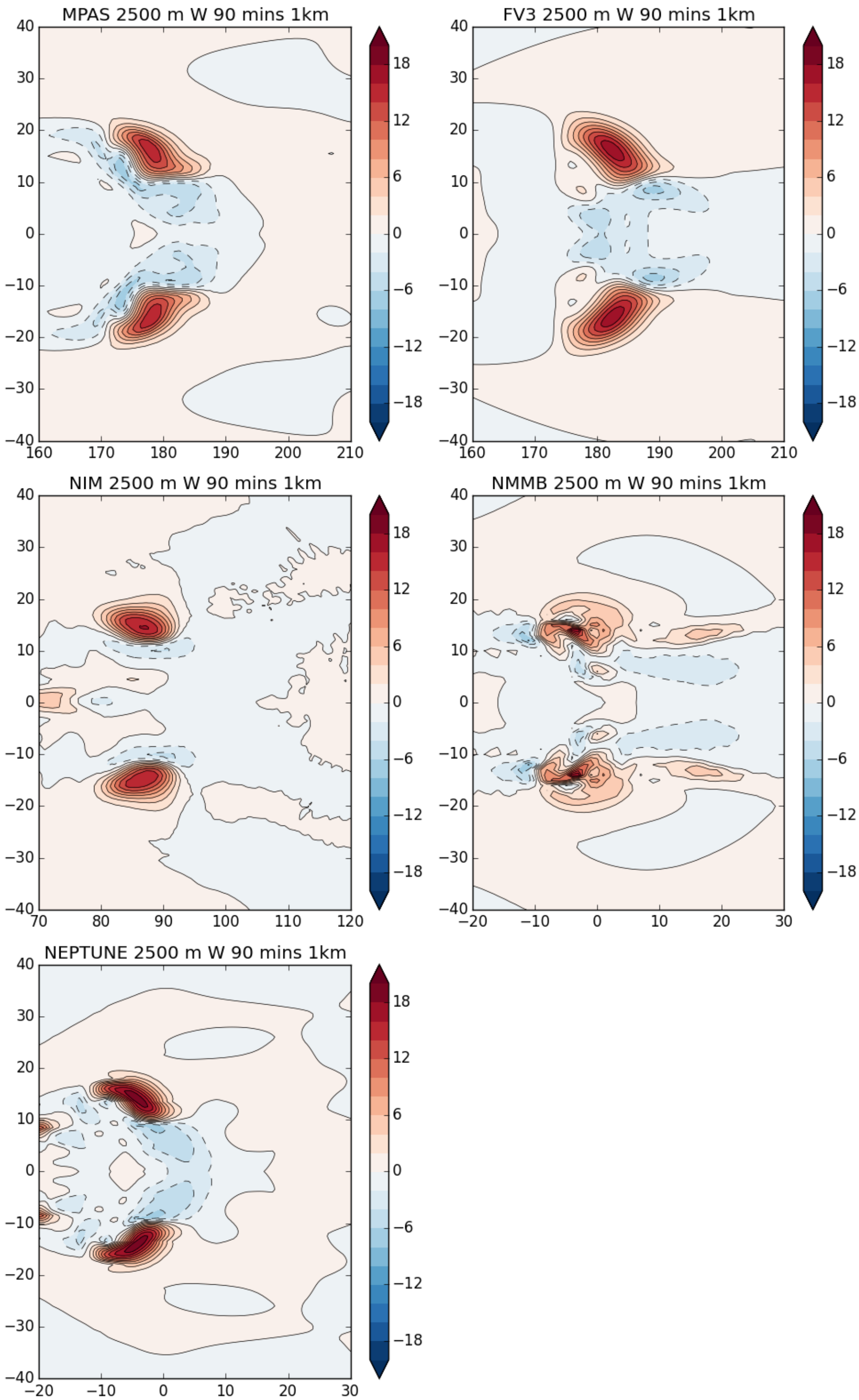

Figure B- 17 As in Figure 16, for the 1-km resolution runs.

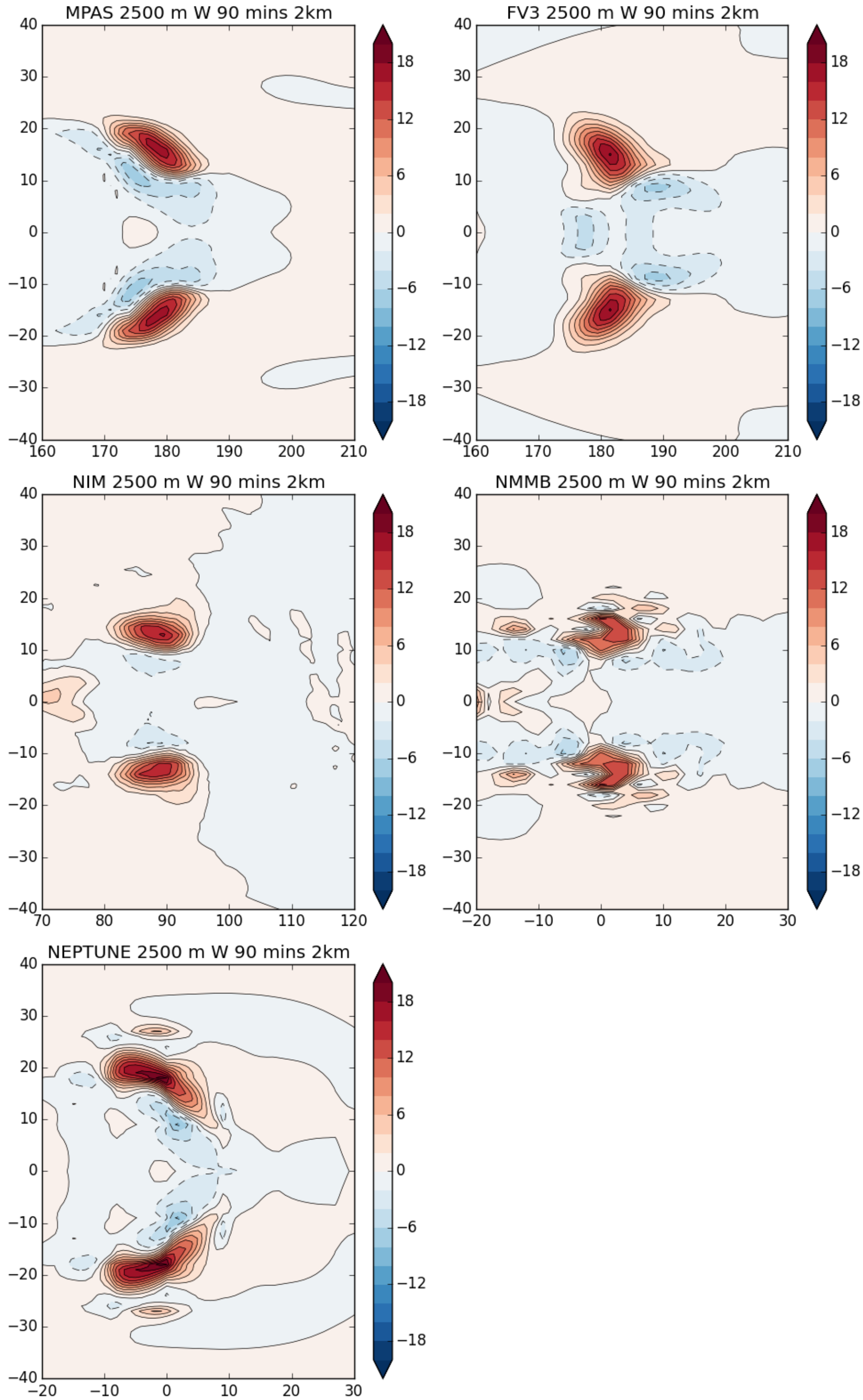

Figure B-18 As in Figure B-16, for the 2-km resolution runs.

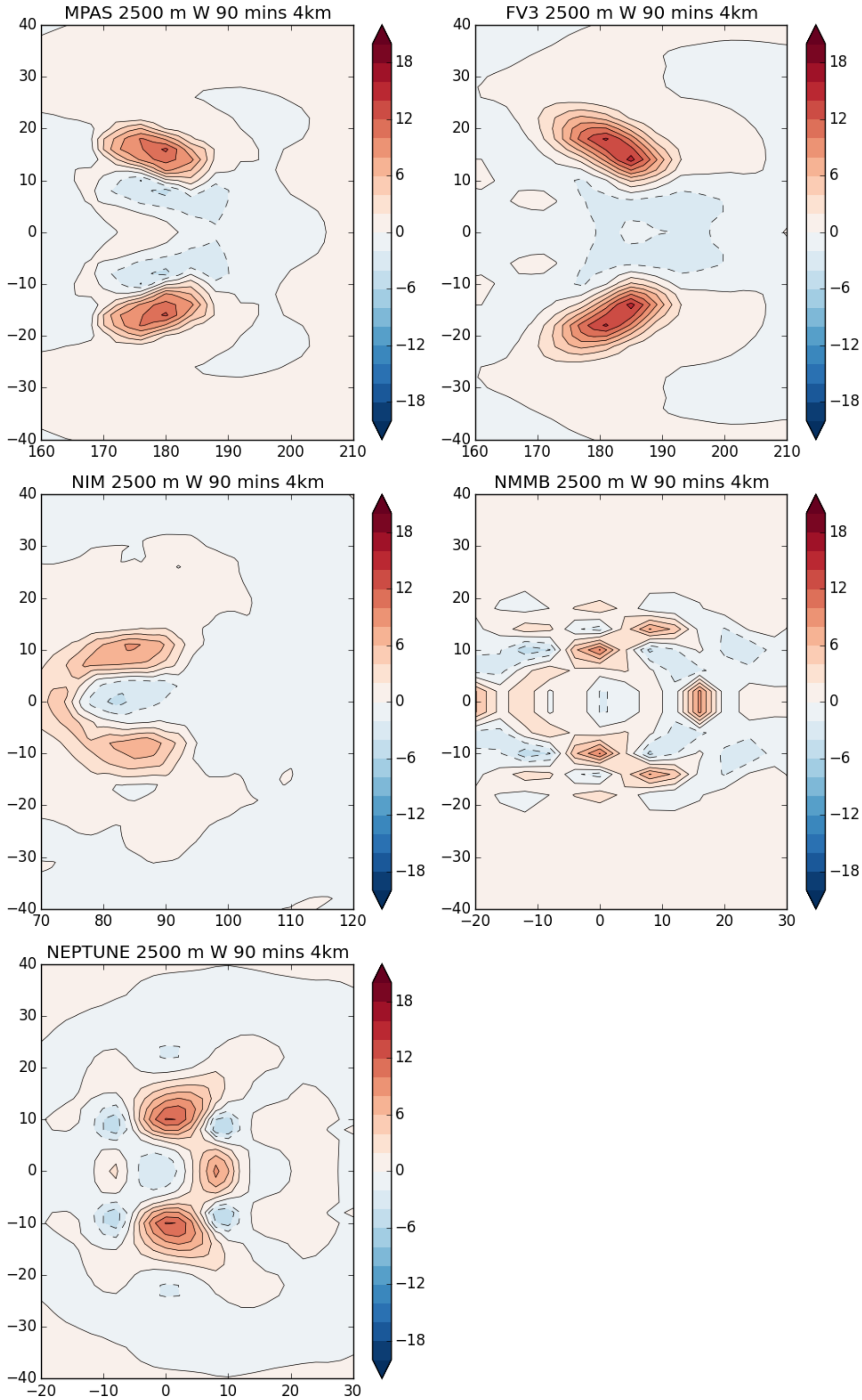

Figure B- 19 As in Figure B-16, for the 4-km resolution runs.